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Pre-Quaternary pollen grains and spores found in late-glacial and post-glacial clays in Bohuslän, SW. Sweden

By MAGNUS FRIES and NILS-ERIK ROSS

With 1 plate and 7 figures in the text

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1. Find circumstances

In connection with a current pollen-analytical research of Late Quaternary deposits in Bohuslän and Dalsland (between the Skagerrak and Lake Vänern, Figs. 1 and 2), some pollen grains were found, which, according to their shape and in some respects their colour, differ from the other pollen examined. All pollen grains in question occur in marine, minerogeneous sediments, as a rule containing a certain amount of secondarily[1] deposited pollen (IVERSEN 1936). Since, however, they could not be identified as belonging to the Late Quaternary Scandinavian flora, it was very probable that the pollen grains found here originated from geological formations earlier than the Late Quaternary, probably from some pre-Quaternary formation. As they showed some similarity to *Eucalyptus* pollen, they were preliminarily named "*Eucalyptus*." These pollen grains, shaped differently from the Scandinavian ones, were later on established by N.-E. Ross as highly resembling special pollen types of Upper Cretaceous age from Scania (see below).

In all, 26 specimens of these pre-Quaternary pollen grains of some different types (Pl. I) were found in seven localities in Middle Bohuslän (Fig. 2).

Two of these localities are supra-marine, each with one pollen find:

1) Bro parish, the peninsula of Härnäset, Kleva mire (c. 10 km NbW of the town of Lysekil) 12 m above the sea (Fig. 2). The pollen, which is of a *Tricolporites protrudens* - type (Pl. I, Figs. 1 and 2), was found in a sample poor in pollen (MF 46/1768) from post-glacial marine clay 5.10 m below the marino-limnic boundary. The mysterious "*Hystrix*"-fossil was very abundant. C. 4 000 Late Quaternary tree pollen grains were registered from 22 analyzed clay samples.

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[1] The term "secondarily" is generally used for characterizing redeposited pollen regardless of how many sedimentation cycles they have been exposed to.

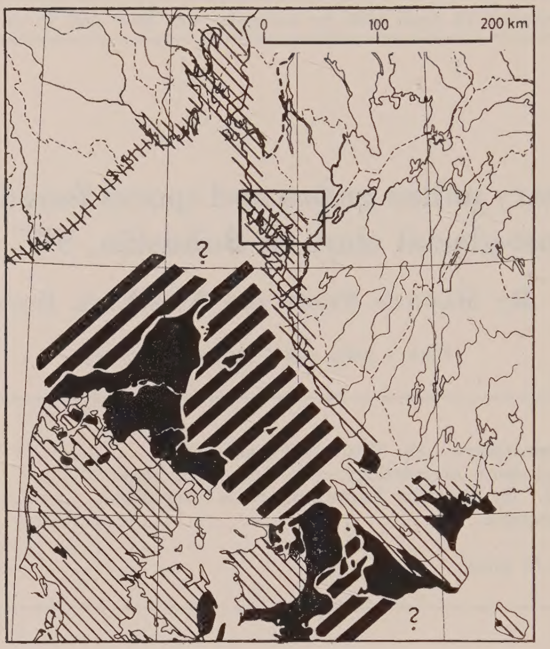

Fig. 1. Map showing the position of the research area between Skagerrak and Lake Vänern (cf. Fig. 2). — Black areas: land areas with Cretaceous in bedrock (according to geological maps). Broad-lined areas: probably Cretaceous in bedrock on the sea bottom (in accordance with occasional suppositions [Bjørlykke 1908, p. 158, Milthers 1909, p. 128, Wiman 1912, p. 486 f., Asklund 1928, Rosendahl 1935]). Fine-lined areas: occurrences (more or less rich) of loose Cretaceous material (according to Ekström 1940, Asklund 1928, Wiman 1912, Rosendahl 1942, and others).

2) Bro parish, Rör mire (c. 2.5 km N of Hallinden railway-station) 115 m above the sea, but below the highest marine limit (Fig. 2). The recognized pollen is of the type pictured in Pl. I, Fig. 6. The sample in question (MF 46/530) consists of a marine clay (also with coarser minerogene material and shell fragments) of late-glacial or, more precisely, finiglacial age. "*Hystrix*" is rather common. From this locality 26 samples have been analyzed, and c. 2 500 tree pollen grains have been registered. In these layers other pollen also exist, which probably are alien to this more or less tundra-like late-glacial vegetation, thus seeming to originate from some interglacial forest vegetation, such as *Alnus* and *Corylus*.

One pre-Quaternary pollen grain (pictured in Pl. I, Fig. 9) has been found in one of the sediment catches, which were hung out by Dr. F. Koczy in the sea-water outside Bornö Research Station at the Gullmar Fiord, Dec. 1944 – Nov. 1945, at a level of 5 m above the muddy clay bottom and 28 m below sea level. In the material deposited in these catches, "*Hystrix*," also considered to be a pre-Quaternary organism (Iversen 1936, 1937), occurs rather frequently (cf. also Erdtman 1949, p. 55). This fact seems to indicate that it is still living in a marine milieu. Nevertheless, through the find of this ancient pollen, it is thus established that "*Hystrix*" is possibly also secondarily deposited in recent sediments. In this case, however, it

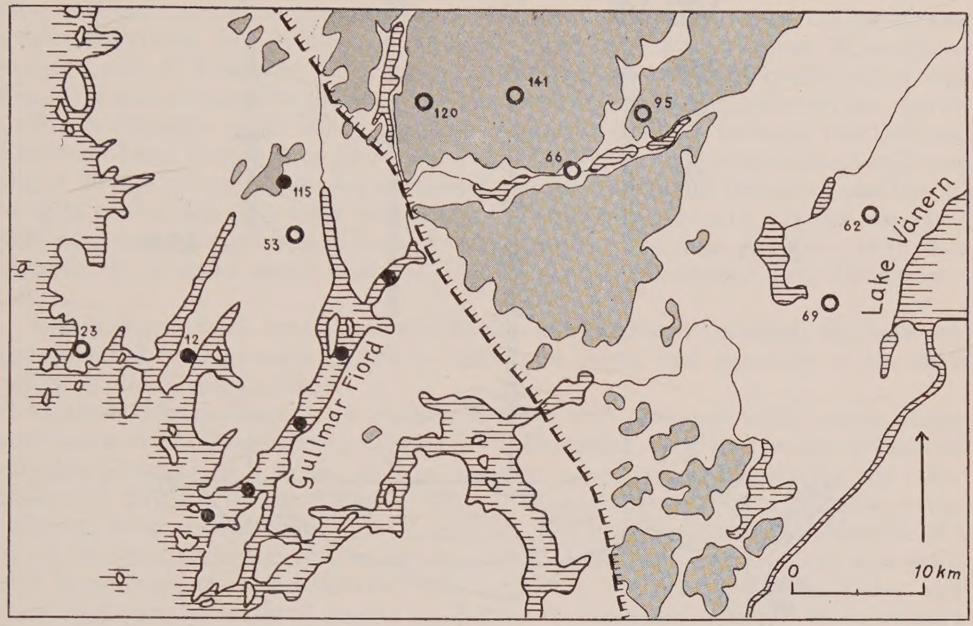

Fig. 2. Map of the research area between Skagerrak and Lake Vänern. — Black dots: localities where pre-Quaternary pollen grains were found. Circles: localities where such pollen grains were sought for but not found. Grayish: areas 100 m or more above the sea. The figures indicate the height in meters above sea-level. The broken line running NNW–SSE: important late-glacial ice-border line ("the great gotiglacial west-coast line," according to BJÖRSJÖ 1949). P. S. The circle 66 ought to be a black dot (cf. Addendum p. 210).

ought to be very abundant in till ashore. In order to ascertain this, some till samples from the Island of Stora Bornö were examined microscopically, though with a negative result in this respect.

The other pre-Quaternary pollen grains were found in sediment cores, which in 1945 had been taken out from the thick bottom sediments of the Gullmar Fiord with the "piston core sampler" of the Oceanographic Institute in Gothenburg (KULLENBERG p 1947). Eight sediment cores were taken up, five of which have been examined pollen-analytically. Altogether, about 350 samples were microscopically examined, and c. 90 000 tree pollen grains registered. Thus the pre-Quaternary pollen grains are very rare. They constitute about 1/4 ‰ of the tree pollen sum. With regard to the possibility of the Late Quaternary pollen production dominating over scattered and possibly long-distance-transported remains of an ancient pollen flora, this value is, however, remarkably high. The map (Fig. 2) shows the geographical position of the sediment cores investigated. Fig. 3 indicates, among other things, the length of the cores and the bottom configuration. The sediment material consists of muddy marine clay sometimes with coarser minerogene material. The sedimentation of the layers taken up in the piston core sampler occurred during the post-glacial age. The find samples vary in their composition as they can consist of more minerogene as well as of more muddy material, and do not deviate from other samples. The distribution of the pre-Quaternary pollen grains among the different

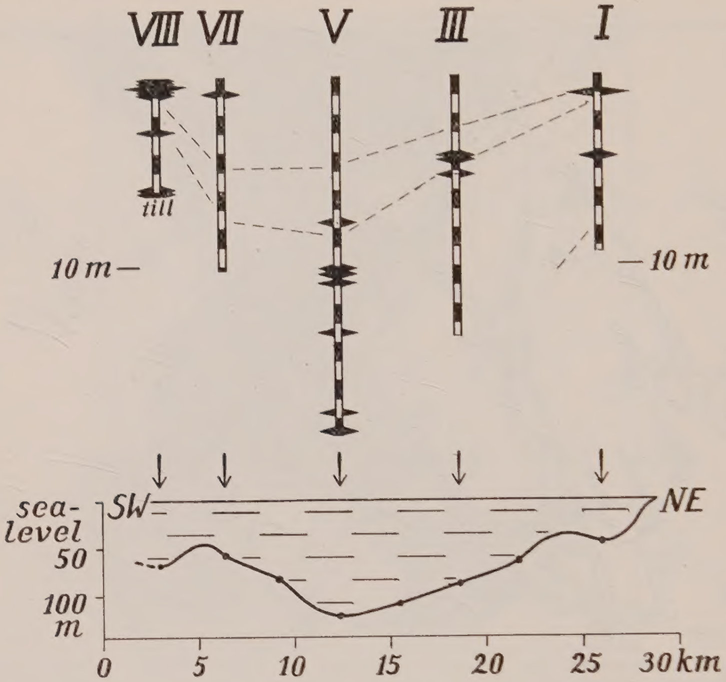

Fig. 3. Above: The sediment cores from the bottom of the Gullmar Fiord, which were pollen-analytically more closely examined; length relations unchanged. The fine, broken lines indicate probably synchronous, pollen-analytical index levels. The bigger transverse signs mark samples having two observed pre-Quaternary pollen grains; the smaller ones, samples with only one grain found (i.e. more or less, resp., than about $^1/_2$ % of Late Quaternary tree pollen grains).

Below: The bottom configuration of the Gullmar Fiord; the Fiord threshold between sediment cores No. VII and VIII.

sediment cores and their position in each core are shown in Fig. 3, where the cores are reproduced with their original relations in length. The fine broken lines reveal probably synchronous layers pollen-analytically established. The core situated close to the Skagerrak and outside the Fiord threshold contains most of the finds (9 pre-Quaternary pollen grains of c. 20 000 Late Quaternary tree pollen registered). Some enrichment at different levels can furthermore be established. This fact may give rise to the presumption that, at times, the erosion reached deposits for some reason especially rich in pre-Quaternary material. (It may, however, be pointed out that somewhat more pollen has been counted in the samples from the uppermost meter in series VIII than in other cases.) In spite of this it would, on account of the scarcity of the finds, be precipitate to attribute any certain tendency to the appearance of pre-Quaternary pollen grains in the bottom sediments from a geographical as well as from a chronological point of view. The pollen of the type pictured in Pl. I, Fig. 7, is the most common in Gullmar Fiord material. — Some trilete spores, which during the first analyses were interpreted as *Sphagnum* spores, belong certainly to some pre-Quaternary *Pteridophyta*-types (cf. Chap. 2 and Pl. I, Figs. 12–19; see also Ross 1949 Pl. I). These spores seem to be more common than the pre-Quaternary pollen grains.

In some pollen-analytically examined late-glacial and post-glacial clay deposits (the localities marked on the map Fig. 2 with figures 53 and 23, resp., indicating the height above the sea) NW of the Gullmar Fiord with totally about 90 analyzed samples and 17 000 tree pollen grains registered, no pre-Quaternary pollen was found. Six more easterly situated late-glacial and post-glacial, more or less clayey sediment deposits — all below the highest marine limit — between the Gullmar Fiord and Lake Vänern were also examined. In all, about 200 samples were analyzed and c. 35 000 tree pollen grains registered. No alien pollen of that kind was found, in spite of the fact that these very sediments sometimes contain a rather considerable number of secondarily deposited pollen grains. The same negative result was obtained by a great many analyses without specially recording Late Quaternary pollen.

Within the research area (Middle Bohuslän and Southern Dalsland) the finds are concentrated to the coastland rich in faults and joints, and especially to the deep valley of the Gullmar Fiord.

As appears from Chap. 3, no position is taken with reference to the causes of the occurrence of pre-Quaternary pollen grains in Bohuslän. Only an account of the conceivable alternatives is given. It may, however, — especially considering the eventuality of drift-ice transport (see p. 208) — be appropriate to pay attention to the following geographical conditions (cf. Fig. 2). The find localities are situated to the W of the geomorphological line running NNW–SSE, partly interpreted as a fault and thrust-fault scarp (LJUNGNER 1927, p. 217 ff.), which separates the higher and somewhat more level inland area in the E from the coastland, which is on an average lower and more broken up. The inland area is mostly situated below the highest marine limit (here about 160 m above the sea) though more or less closely below this limit. Further, it may be observed that, in connection with the terrain line mentioned above, there is the continuation northwards of the Gothenburg moraine (Sund–Svarteborg–Tanum) or "the great gotiglacial west-coast line" (BJÖRSJÖ), signifying an ice-border position during perhaps a long interstage period (BJÖRSJÖ 1949, p. 288, 303, 320). The still uncertain connection southwards to ice-movements and ice-melting in Scanodania (cf. WENNBERG 1949) make it at present impossible to reconstruct the geographical situation at the time of possible drift-ice transport. — The striae indicate an ice-movement direction from NE or ENE, later during the deglaciation more and more strongly influenced by the underlying terrain (DE GEER 1910, BJÖRSJÖ 1949).

2. Pollen and spore morphology

Pollen grains

The tricolporate and tricolpate pollen grains here described are all easily distinguished from Quaternary grains by their protruding germ apertures and their thick exines, which must have favoured their "survival" during erosion and redeposition processes.

R. POTONIÉ (1934) and THIERGART (1940 and 1942) were the first to draw attention to these pollen types ("*Eucalyptus*-ähnlicher Typ," some types of *Pollenites Pompeckiji* R. POT. and some of *Pollenites vestibulum* R. POT.). Later they were also found in Sweden (ROSS 1949). They seem to characterize the Upper Cretaceous pollen flora. However, they also turn up in Palaeocene and Eocene strata, but then disappear (according to THIERGART 1940, p. 17).

Three pollen grains from Bohuslän are referred to *Tricolporites protrudens*, the holotype of which was recently described by ERDTMAN (in ROSS 1949, p. 37). The *T. protrudens* - types seem to be a rather unitary morphological group, especially with regard to their thick inner exine layers, which form distinct vestibuli inside the colpae. The two other types described differ from the *Tricolporites protrudens* - types mainly due to their lack or faint development of vestibuli.

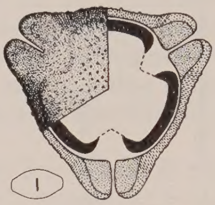

Fig. 4. *Tricolporites protrudens* - type Pl. I, Fig. 1. Polar view c. 1 000 ×, equatorial view c. 250 ×. Half-schematic drawing.[1]

Pl. I, Fig. 1.

Diagnosis. Pollen grains tricolporate, of small to medium size (equatorial diam. 25–28 μ), probably oblate. Exine indistinctly reticulate. Colpae short with square ends. Besides the smaller size, the main difference from ERDTMAN's specimen consists in the heavy exine thickenings which nearly fill the small chambers (vestibuli) between the outer and inner openings.

Occurrence. Three specimens were obtained somewhat differing with regard to exine thickness. The two pictured grains (Pl. I, Figs. 1 and 2) were found in post-glacial sediments in the Gullmar Fiord, the third specimen in a post-glacial clay from the Kleva mire, Bro parish, Bohuslän.

Pre-Quaternary references. The Upper Cretaceous Åsen deposit, Scania, is rich in various *Tricolporites protrudens* - types. The specimen pictured in Pl. I, Fig. 3, seems to be identical with, or at least very closely related to the present type.

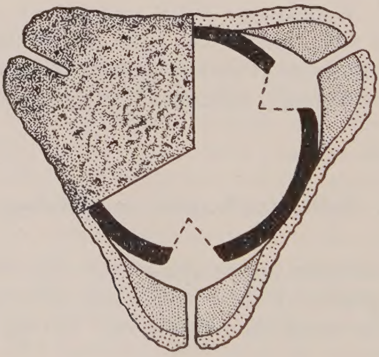

Fig. 5. *Tricolporites protrudens* - type Pl. I, Fig. 4. Polar view c. 1 000 ×. Half-schematic drawing.

Pl. I, Fig. 4.

Diagnosis. Pollen grains tricolporate of medium size (equatorial diam. c. 43 μ), probably oblate. Exine with distinct, irregularly sculptured pattern. Heavy exine thickenings at the apertures as in the preceding type.

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[1] All pictured pollen grains and spores derive from samples treated with hydrofluoric acid and then acetolysed. The drawings of the pollen grains are chiefly made in accordance with the manner used by G. ERDTMAN.

Occurrence. One specimen from the post-glacial clay of the Gullmar Fiord. A similar pollen grain was also obtained from a Scanian clayey till of Torrlösa (Pl. I, Fig. 5).

Pre-Quaternary references. No specimen identical with the present one has been observed among the Åsen *Tricolporites protrudens* - types.

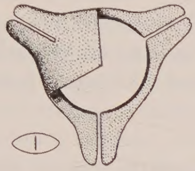

Fig. 6. Tricolpate pollen grain Pl. I, Fig. 6. Polar view c. 1 000 ×, equatorial view c. 250 ×. Half-schematic drawing.

Pl. I, Fig. 6.

Diagnosis. Pollen grains tricolpate, of small to medium size (12 × 26 μ), peroblate. The thick exine devoid of sculpture and, in section, rather homogeneous. Heavy, protruding exine thickenings at the apertures. Colpae short with square ends.

Occurrence. In post-glacial clays from the Gullmar Fiord and in a late-glacial clay from the Rör mire, Bro parish, Bohuslän (see above, p. 200).

Pre-Quaternary references. THIERGART pictured a similar pollen grain isolated from a Palaeocene or Upper Cretaceous sediment from the Province of Hannover (1940 Taf. XII, Fig. 24: "*Eucalyptus*-ähnlicher Typ." Equatorial diam. c. 30 μ).

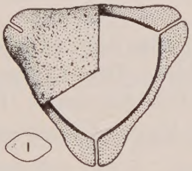

Fig. 7. Tricolpate pollen grain Pl. I, Fig. 7. Polar view c. 1 000 ×, equatorial view c. 250 ×. Half-schematic drawing.

Pl. I, Fig. 7.

Diagnosis. Pollen grains tricolpate or tricolporate (this is due to the presence of endexinous depressions bearing an inner opening inside each colpa), of small to medium size (c. 16 × 25 μ), oblate. Exine indistinctly sculptured. Colpae short with square ends. Heavy exine thickenings at the apertures. In some specimens there were observed faint indications of endexinous depressions forming vestibuli.

Occurrence. This type seems to be the most common pre-Quaternary pollen grain of the post-glacial clays from the Gullmar Fiord.

Pre-Quaternary references. One pollen grain observed in an Eocene sediment from Åhus, Scania, is closely related to the present type. Similar grains also occur in the Upper Cretaceous Åsen deposit.

Pl. I, Fig. 10.

Diagnosis. See Ross 1949, p. 36.

Occurrence. The pictured specimen observed at Prof. L. VON POST's investigations of the Quaternary deposits of the Viskan Valley, SW. Sweden (see further p. 207). Some specimens observed in Early Dryas clay from the Island of Bornholm (according to information by Dr. J. IVERSEN).

Pre-Quaternary references. Pollen grains identical with the present type occur in the Upper Cretaceous Åsen deposit, Scania ("*Tricolpites aspidatus* f. *tricirculata*" Pl. I, Fig. 11).

Spores

Besides the pollen grains described above, several spores of true pre-Quaternary age were also found in the cores from the Gullmar Fiord. Here follows a description of mainly those that can be referred to known pre-Quaternary types.

Pl. I, Fig. 12.

Diagnosis. Spores trilete of medium size (c. 48 μ). Laesurae of the tetrad scar very distinct and reaching the angles. Exine smooth.

Occurrence. A few specimens obtained from post-glacial clays of the Gullmar Fiord.

Pre-Quaternary references. This spore seems to coincide with certain "Schizaeaceen- oder Cyatheaceenspore" reported by THIERGART (1940), e.g. *Sporites Neddeni* R. POT. (op. cit., Taf. I, Fig. 2). The latter is a very wide-ranging type occurring from the Carboniferous to the Recent (according to THIERGART 1949, p. 11).

Pl. I, Fig. 13.

Diagnosis. Coincides in general with the preceding type, but is smaller (c. 27 μ). Walls somewhat contracted in the pictured specimen.

Occurrence. Only one specimen obtained from a post-glacial clay of the Gullmar Fiord.

Pre-Quaternary references. Also this type can be included in *Sporites Neddeni* sensu THIERGART (e.g. *S. Neddeni*, ältere Form, Taf. IV, Fig. 2; Miocene). Closely related spores, interpreted as *Gleicheniidites* (ROSS 1949, Pl. I, Fig. 3), also occur abundantly at one level of the Upper Cretaceous Åsen deposit.

Pl. I, Fig. 14.

Diagnosis. Spores trilete of medium size (c. 31 μ). Tetrad scar distinct. In polar view a broad (exinous?) ring is visible that seems to be limited to the equator.

Occurrence. A few specimens were obtained from the post-glacial clays of the Gullmar Fiord, and from a Baltic moraine clay at Torrlösa (near Svalöv), Scania.

Pre-Quaternary references. Spores of this type occur in the Upper Cretaceous Åsen deposit (Pl. I, Fig. 15). I have found no descriptions of similar Tertiary spores.

Pl. I, Figs. 17–18.

Diagnosis. Spores trilete of medium size. Laesurae of the tetrad scars reaching the angles. Exine covered with coarse projections.

Occurrence. Two specimens (apparently not closely related to each other) from post-glacial clays from the Gullmar Fiord.

Pre-Quaternary references. Trilete, warted spores occur in the Åsen deposit. No spore hitherto interpreted is, however, identical with any of the two described above.

3. Discussion

As pointed out in the preceding chapter, two of the five redeposited pollen types described there are identical with specimens found in an Upper Cretaceous deposit of Åsen, Scania. The other three types are closely related to various Åsen specimens. In Germany, THIERGART, too, found these ancient pollen types — summed up under the name of "Dreiecksformen" — from Upper Cretaceous deposits (cf. THIERGART 1949, Taf. IV/V, Fig. 59); but most of those "Dreiecksformen" recorded by THIERGART derive from Palaeocene clays obtained from borings in the Province of Hannover (op. cit., Taf. IV/V and THIERGART 1940, Taf. XII). The age of the Hannover sediment has, however, also been interpreted as Cretaceous (cf. THIERGART 1940, p. 17). Nevertheless, it seems to be well established that some types of the present pollen grains are rare in early Tertiary stages, viz. the Palaeocene and the Eocene (cf. e.g. the specimen from an Eocene clay of Åhus, Scania; Pl. I, Fig. 8).

Thus only Upper Cretaceous and, in a less degree, early Tertiary deposits may be taken into consideration in our search for the possible sources of the present redeposited pollen grains. As to Scanodanian Palaeocene and Eocene deposits, only the pollen flora of the Eocene clay of Åhus has been investigated (Ross, unpublished). The pollen content of this sediment was very scanty, mainly consisting of *Pinus* and *Carya* pollen. Only one specimen comparable with the "Dreiecksformen" has hitherto been obtained. It is therefore more probable that the ancient pollen grains of the Quaternary clays of Bohuslän and other localities in Southern Sweden and Denmark should originate from Upper Cretaceous sediments similar to the clayey Åsen deposit, which in some levels is rich in various types of "Dreiecksformen."

Outside the above Bohuslän area the following finds of similar pollen grains secondarily deposited are known to the authors:

1) One pollen grain ("*Tricolpites aspidatus* f. *tricirculata*," see Pl. I, Fig. 10) found in Prof. L. VON POST's investigations of the Late Quaternary, marine sediments from the Viskan Valley, SW. Sweden, c. 125 km SSE of the Gullmar Fiord (further details unknown).

2) Some pollen grains of *Tricolporites protrudens*-type in Baltic clayey till from Scania, Torrlösa parish, Östraby (Pl. I, Fig. 5); trilete spores and "*Hystrix*" of different types are common. — One pollen grain from Scania (communicated by ERDTMAN in ROSS 1949, p. 37); the locality and the age of the find stratum unknown. — In the SW. Scanian till, rich in Cretaceous material, Dr. E. MOHRÉN has also found some pollen grains of the types in question.

3) Some pollen grains ("*Tricolpites aspidatus* f. *tricirculata*") from the Island of Bornholm, found in Early Dryas clay (communicated by Dr. J. IVERSEN).

4) Several pollen grains from some places in Denmark proper: in clayey till, from where they have been removed and redeposited in late-glacial clays (IVERSEN's "*Triangularia*" 1936, p. 9, the same as the "*Tricolpites aspidatus*"-type in ROSS 1949, Pl. III, Fig. 43).

In the Gothenburg investigation by MOHRÉN (1945) no pollen grains of "*Triangularia*"-type were found (p. 253).

Considering the geographical distribution of pre-Quaternary pollen — of course still imperfectly known — in the areas discussed above, one is inclined to compare these occurrences with the loose Cretaceous material outside the area of the Cretaceous, the former of which occurs more or less abundantly in the areas in question.

In Fig. 1 there is a reproduction of areas having Cretaceous in bedrock, more or less known, as well as of those areas where loose Cretaceous material (boulders of limestone and flint) occurs.

The reasons for the prevalence of the loose Cretaceous material have occasionally been discussed in literature. Here only such main points of view will be referred to as — especially regarding Bohuslän — have been dealt with in this connection (see also WIMAN 1912, p. 476).

On the one hand, ever since OLBERS (1866, p. 14 f.) and, above all, DE GEER (1884, p. 457 f.) Cretaceous limestone and flint boulders are mostly supposed to have been transported there by icebergs during deglaciation from areas with Cretaceous in bedrock (cf. also int. al. HOLTEDAHL and others 1934, p. 365, and ROSENDAHL 1935, 1942). The occurrences along the Swedish west coast are also, in accordance to this, limited to areas below the highest marine limit. (Cf. however EICHSTÄDT, 1909, as to some finds of flint — on the soil surface — partly N of the Middle Swedish terminal moraines, and partly S of them, but above the marine limit.) However, it is *a priori* not necessary to assume the Cretaceous pollen as having been included in this transport. By support of the appearance of the Scanian pollen grains, which are mostly identical, there is good reason to suppose that also Cretaceous pollen found on the west coast was originally embedded in Upper Cretaceous clays. Such material seems to be less suitable for long-distance transportations in this manner. If, however, this theory of long-distance transport is correct, and can also be applied to the Cretaceous pollen grains, it follows that even part of the clay in which the pollen grains are now embedded consists of material of Scanodanian origin. — A conception somewhat divergent is given, concerning SW. Norway (Jæren), by BJØRLYKKE (1908, p. 45 and 158), who considers the Cretaceous material occurring there to be transported by a Skagerrak glacier during the great (Riss) glaciation (cf. MILTHERS 1911, p. 511, and also HORN & ISACHSEN, 1943, as to Jurassic coal in till of Jæren).

On the other hand, ERDMANN (1868 a, p. 14, 1868 b, p. 16), LJUNGMAN (1870), and EICHSTÄDT (1908), basing their opinion on finds of Cretaceous boulders of limestone and flint in moraine and glacifluvial material, maintained that their finds originate from a preexistent Cretaceous formation on the Swedish west coast. With regard to Halland, ASKLUND (1928, p. 804 ff.) has advanced the probability of some local remains of the Cretaceous still being preserved in sheltered localities. According to this opinion, these pollen-bearing sediments of Bohuslän consist, to perhaps no inconsiderable an amount, of Upper Cretaceous (and Palaeocene?) clay material, which may, with its fossil content, have been the object of several redepositions here. The support of this interpretation is perhaps to be found in the undermost bottom sediments of the Gullmar Fiord, hitherto impossible to reach, or in other deep valleys following faults and joints on the coast.

Finally, there must be considered the possibility of the pollen grains having been transported successively by sea currents, at least in certain stretches.

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SENDAHL (Oslo) who has confirmed the correctness of the map in Fig. 1, as to the Norwegian area. I, the undersigned M. FRIES, wish to thank Miss M. SIKSNA and Mr. TH. CANDOLIN, my collaborators at the microscope. Finally, it may be added with gratitude that the expenses for the pollen analyses are mostly covered by a grant from the "Kungl. och Hvitfeldtska stipendieinrättningen," Gothenburg.

Institute of Palaeontology, Uppsala University, April 1950.

Magnus Fries. *Nils-Erik Ross.*

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Explanation of plate

Magnification about 820 ×. All slides recorded below are kept in the Palaeont. Inst. of Uppsala Univ. The photographs are taken by N.-E. Ross. — Boh. = Bohuslän; Hall. = Halland; Sk. = Skåne (Scania); sec. = secondarily deposited. All pictured pollen grains and spores derive from samples treated with hydrofluoric acid and then acetolysed.

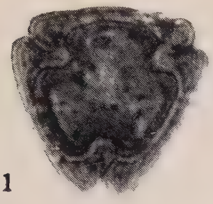
Fig.	Locality	Slide
1. *Tricolporites protrudens* - type	Boh., Gullmar Fiord, core VIII (sec.)	MF 45/VIII 1960
2. *Tricolporites protrudens* - type	do., core I (sec.)	MF 45/I 1856
3. *Tricolporites protrudens* - type	Sk., Näsum par., Åsen	Åsen I: 31
4. *Tricolporites protrudens* - type	Boh., Gullmar Fiord, core V (sec.)	MF 45/V 170
5. *Tricolporites protrudens* - type	Sk., Torrlösa par., Östraby (sec.)	Torrlösa 1
6. Tricolpate pollen grain	Boh., Gullmar Fiord, core VIII (sec.)	MF 45/VIII 2078
7. Tricolporate or tricolpate pollen grain	do., core VIII (sec.)	MF 45/VIII 2068
8. Tricolporate or tricolpate pollen grain	Sk., Åhus	Åhus 2214: 1
9. Tricolporate or tricolpate pollen grain	Boh., Gullmar Fiord, catch outside Bornö Research Stat. (sec.)	Bornö, tratt 2
10. "*Tricolpites aspidatus* f. *tricirculata*"	Hall., Viskan Valley (sec.)	—
11. "*Tricolpites aspidatus* f. *tricirculata*"	Sk., Näsum par., Åsen	Åsen I: 1
12. Trilete spore	Boh., Gullmar Fiord, core VIII (sec.)	MF 45/VIII 2036
13. Trilete spore	do., core V (sec.)	MF 45/V 166
14. Trilete spore	do., core VIII (sec.)	MF 45/VIII 1954
15. Trilete spore	Sk., Näsum par., Åsen	Åsen I: 35
16. Trilete spore	Boh., Gullmar Fiord, core ? (sec.)	—
17. Trilete spore	do., core VIII (sec.)	MF 45/VIII 2014
18. Trilete spore	do., core V (sec.)	MF 45/V 108
19. Trilete spore	do., core V (sec.)	MF 45/V 24

Addendum

During the printing of this paper Mr. Th. Candolin found another specimen of a Cretaceous pollen in a late-glacial clay sample (MF 46/1103) from a locality of special interest: Dalsland, Valbo-Ryr parish, the bog at Ramhult (just W of Elnesjön), about 66 m above sea-level. The pollen grain is of the type pictured in Pl. I, Fig. 1. The locality is situated in the inland area E of the late-glacial ice-border line, which was mentioned above as a possible eastern limit for the dispersal of Cretaceous pollen grains along the coast. This interpretation is thus not relevant. It might, however, be observed that the find was made in minerogene material from the bottom of a valley running W—E through the high inland area (cf. map Fig. 2). From Lake Elnesjön in this valley there is also reported an isolated find of flint boulder (Eichstädt 1908, p. 109).

Tryckt den 31 oktober 1950

Uppsala 1950. Almqvist & Wiksells Boktryckeri AB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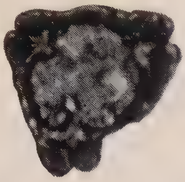
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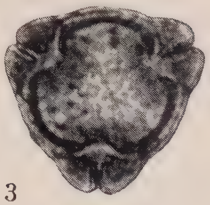
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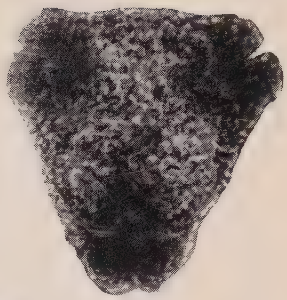
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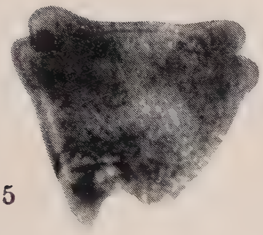
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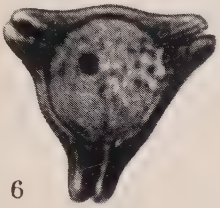
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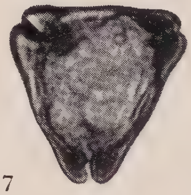
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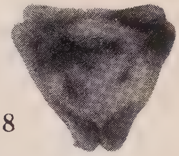
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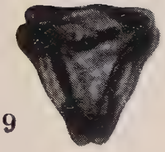
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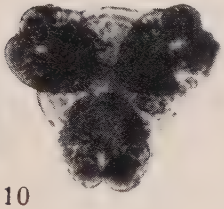
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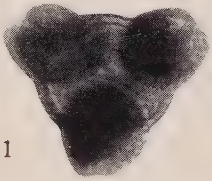
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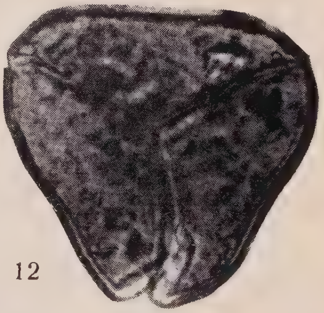
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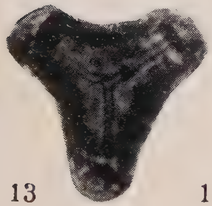
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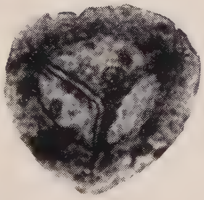
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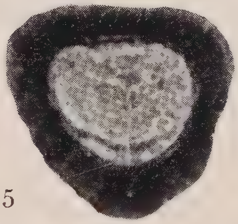
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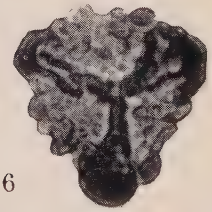
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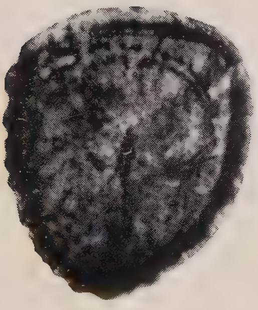
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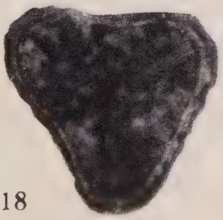
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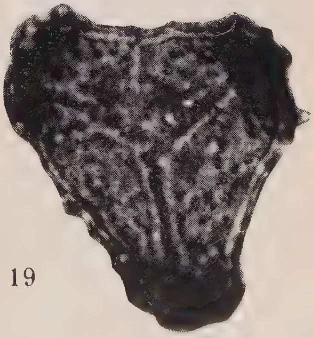
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ARKIV FÖR MINERALOGI OCH GEOLOGI Band 1 nr 8

Communicated 7 June 1950 by Erik Stensiö and Nils Holmgren

On some vertebrate fossils from Gotland with some comments on the stratigraphy

By Nils Spjeldnæs

With 1 plate and 2 figures in the text

During his field work in Gotland the last two summers (1948—1949), the author also found some remains of vertebrates in two new localities (Fig. 1). In one of these localities, Lau Backar, a large number of samples were taken from layers which might be expected to contain vertebrates. The samples were treated with diluted acetic acid in order to dissolve the carbonates. The insoluble rest of several kg. of rock contained some 20 scales, some indeterminable remains of vertebrate hard tissues, and also a large number of phosphatic pieces of invertebrates, chiefly Brachiopods, Bryozoans, Conodonts, and Phyllocarids.

The other new locality is a small grinding-stone quarry in the Burgsvik sandstone, approximately 1.5 km. south of Grötlingbo railway station, at Sallmunds in the parish of Grötlingbo (Fig. 2). The vertebrate fossils found in this quarry are relatively large fragments of Cephalaspids and other lower vertebrates. All the vertebrate fossils occur in one layer of sandstone which is rich in clay pellets. The bedding is quite irregular and the layer has possibly been exposed to prediagenetic movements (subaqueous slides). This rock is unsuitable as a grinding-stone, and is consequently discarded in the quarry. *Homalonotus knighti* and *Dolerorthis rustica* are the only invertebrates met with in the vertebrate-yielding layer.

Description of fossils

Indeterminable Cephalaspid

(Pl. I, figs. 8—9)

The largest specimen found at Grötlingbo is a fragmentary ventral rim of a Cephalaspid, indeterminable as to species, genus and family. The cephalic shield to which the rim belonged must have been about 6 cm. broad, and is consequently the largest one so far met with in the Baltic area. Some minor fragments found show an ornamentation similar to that of the ventral rim.

Acanthodian scales

(Pl. I, figs. 6—7)

The vertebrate material from Lau Backar comprises about 10 Acanthodian scales belonging to the *Nostolepis* type and the *Gomphodus* type (Gross 1947).

The first type is represented by a single, small scale. The scales of the *Gomphodus* type vary a good deal with regard to the height in an apico-basal direction. The constriction between the base and the crown may be more or less pronounced. All the *Gomphodus* scales discussed here have a smooth crown.

Coelolepid scales

(Pl. I, figs. 1—5)

The material available contains at least 11 Coelolepid scales, 10 of which are from Lau Backar, while one comes from Grötlingbo. They are of different types, some of them resembling the *Lanarkia* type (Pl. I, Fig. 4). The single scale from Grötlingbo is suggestive of the one shown in Pl. I, Fig. 2, but has well-marked grooves and ridges on the constriction between the base and the crown.

The invertebrate fauna

The invertebrate fauna associated with the vertebrates has not been studied in detail as yet. As the few invertebrates found at Grötlingbo have already been mentioned, the following description refers only to the fauna at Lau Backar. Only those of the fauna elements which have phosphatic, silicified or chitinous skeletons are dealt with here. The other faunal elements which have a calcareous skeleton have not been studied. They are chiefly Bryozoans and Brachiopods.

Foraminifera

Agglutinating foraminifera were observed. Most of the fragile specimens have been damaged, but some are well preserved. They belong to several different types, some of them resembling *Thurammina* and *Sorosphaera*. They may, however, possibly not belong to the genera mentioned, and the lack of well-preserved specimens excludes a closer determination.

Polychaete jaws

Only some few Scolecodonts have been found. They belong to the genus *Lumbriconereites* HINDE.

Inarticulate Brachiopods

Several fragmentary valves of inarticulate Brachiopods occur in the material. Some of them belong to the genus *Lingula*, others are thick-valved, with coarse, semi-concentrical ridges.

Bryozoans

The material from Lau Backar contains numerous small, more or less spherical bodies, which are globules of bryozoans (see OAKLEY 1934). Such globules occur commonly in many members of the *Ceramoporidae*. In this case it is of course impossible to determine from which species the globules come. Two species of globule-bearing Ceramoporids are met with in the vertebrate-yielding layer, *Favositella* sp, and *Spatiopora irregularis* HENNIG, but it is probable that the free globules were deposited secondarily.

The larger globules are of an order of size similar that of the Acanthodian scales (0.25–0.50 mm), and often resemble rounded Acanthodian scales as regards their colour and shape. The chemical composition of the globules is the same as that of bone (Carbonate apatite, OAKLEY 1934). Probably because of this, they stain in the same manner as does the vertebrate hard tissue (with methylene blue, picro-fuchsine, and malachite green), and they may therefore be mistaken for corroded fish-scales. Generally, it is very easy to distinguish between globules and scales in thin sections. In some cases, however, the preservation of the internal structures of the scales is poor. Many of the globules have been attacked by algae and "thread moulds" and therefore show canals and small spaces which resemble dentine tubes, bone-cells, etc. These globules and other phosphatic parts of the Bryozoans will be subjected to further study by the author.

Conodonts

Conodonts occur abundantly. They belong to several "genera": *Ozarkodina*, *Prioniodus*, *Drepanodus*, and others. This fairly rich material will be subjected to a further study.

Phyllocarids

Some tooth-like bodies, too, were found in the material. Similar bodies have been described by HARLEY (1861) as *Astacodermata* from the Ludlow Bone-bed. HARLEY (l.c.) seems to regard them as Conodonts. In fact, the "genus" *Astacodermata* appears to comprise both Phyllocarids and Conodonts for *A. serratum* and *A. spinosum* are Conodonts, while the other species most likely comprise material of Phyllocarids. In the material from Lau Backar there is also a large *Ceratiocaris*-spine.

Other fossils

Besides the fossils already mentioned, the author has also found some indeterminable moulds of Ostracods, Lamellibranchs and Gastropods, and a small fragment of a *Pterygotus*.

Earlier records of vertebrates from the Silurian of Gotland

Up to now, the records of vertebrate remains from the Silurian of Gotland have been very meagre. A Cyathaspid (*Cyathaspis schmidti* LINDSTRÖM 1896, non GEINITZ 1884 = *Archegonaspis lindströmi* KIAER & HEINTZ 1932[1]) and Coelolepid scales (SÄVE-SÖDERBERGH 1941, p. 237, footnote 2) have been mentioned. The only reference to Acanthodians is by ROHON (1893), who reported *Gomphodus*

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[1] The statement of KIAER & HEINTZ (1932) that *Archegonaspis lindströmi* comes from the upper Silurian of Scania, is erroneous. Their figured specimen is the holotype of LINDSTRÖM's description and is from Lau Kanal, Gotland, from layers belonging to the Hemse Group.

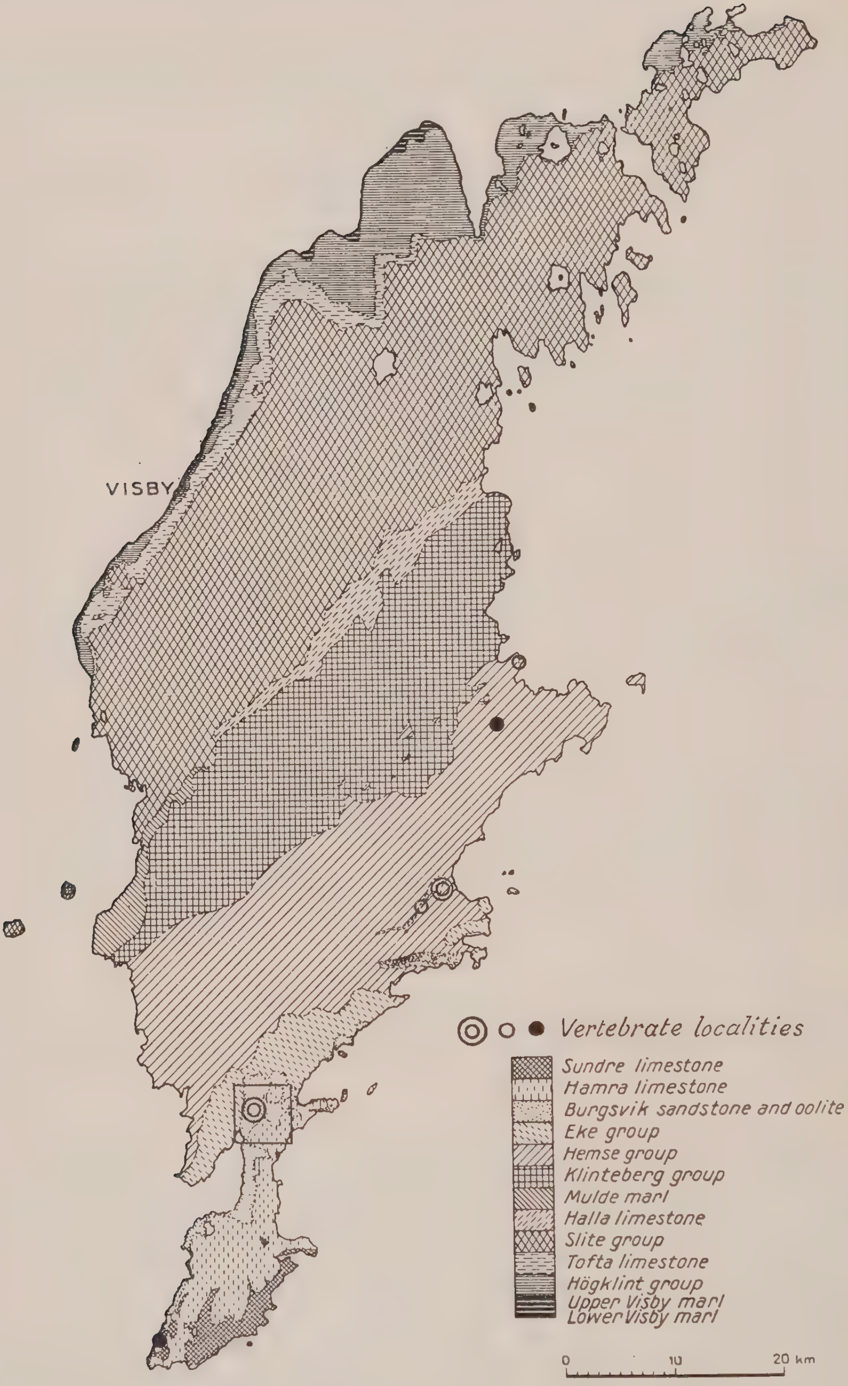

Fig. 1. Geological map of Gotland, showing the distribution of the vertebrate localities. Filled circles indicate uncertain localities, unfilled indicate older, certain ones, and double circles indicate the new localities. The small rectangular area is that shown in fig. 2. The map is from HEDE (1942, fig. 1).

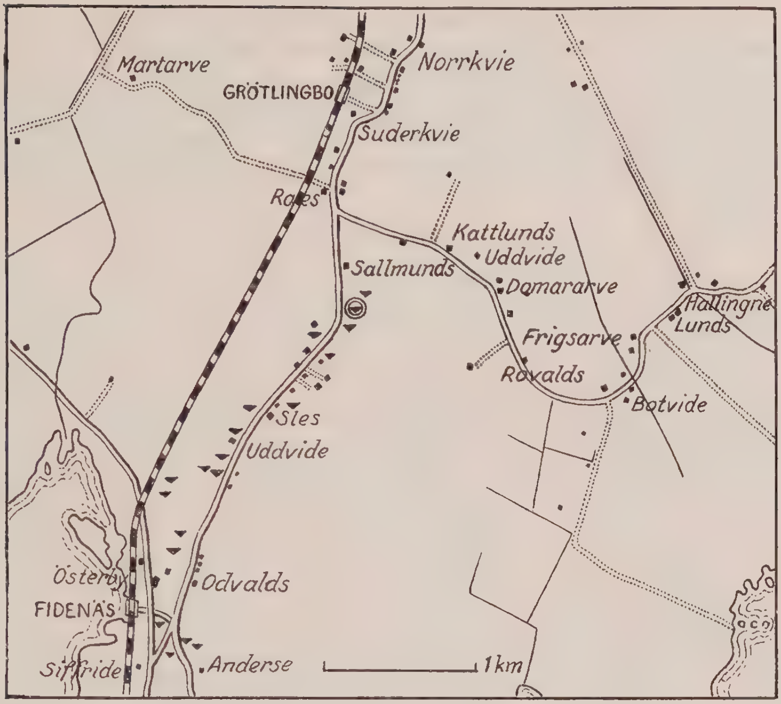

Fig. 2. Map of the new vertebrate locality in Grötlingbo. The quarry is indicated by a double circle. Scale: 1: 50 000. The map is a copy of the geological map "Burgsvik jämte Hoburgen och Ytterholmen", S. G. U. (Swedish Geol. Survey), ser. Aa., nr. 152.

volborthi Rohon and a doubtful fin-spine from Hammarudd in the parish of Kräklingbo. The material referred to by Säve-Söderbergh (l.c.) from this locality as Coelolepids, has been studied histologically by T. Ørvig, who has informed me that three of the five scales labelled "*Thelolepis glaber*" are from Acanthodians, whereas two are from Coelolepids. At least one of the Acanthodian scales belongs to the histological type of *Gomphodus* (*in sensu* Gross 1947).

The exact stratigraphical position of the vertebrate-yielding layer at Hammarudd in Kräklingbo is unknown, but according to the geological maps (Hede *et al.* 1929) this layer probably belongs to the middle or lower part of the Hemse Group (Lower Ludlowian).

Besides the records in the literature, the author has found an unpublished note by Lindström. In an interleaved specimen of his "List of the Fossil Faunas of Sweden II, Upper Silurian" (1888) he has made some additions including some vertebrates from Gotland:

Thelolepis glaber, and *T. parvidens*, Torsburgen and Hammarudd in Kräklingbo (Hemse Group),

Thelolepis glaber, Lau Kanal (Hemse or Eke Group),

Thyestes sp. Hoburgen d. (Upper, oolitic part of the Burgsvik Group).

Except for the scales from Hammarudd, mentioned above, these fossils have not been reported later on, and are unknown in Swedish museums.

Dr. G. WÄNGSJÖ has informed me that a fragment of a *Dartmuthia* has been brought back from Gotland by an excursion with students from the University of Uppsala. It is preserved in the collections of the Palaeontological Institute of the University of Uppsala; both locality and horizon are unknown.

Stratigraphical remarks

In the Grötlingbo locality, the geological features are quite simple. The vertebrate-yielding sandstone-layer is approximately one meter below the oolitic limestone, which usually forms the upper part of the Burgsvik Group.

In the Lau District, the geology and stratigraphy are more complicated. This area has been described by MUNTHE (1902) and HEDE (1925). The vertebrate-yielding layer is also found in the well-known profile of Lau Kanal, some 2 km. south-west of Lau Backar. Here, however, the author did not succeed in finding any doubtless vertebrate remains. Stratigraphically, the layers in question, at Lau Backar and Lau Kanal, belong to the lowermost part of the Eke Group, situated just above the Hemse Group. The boundary between these two groups appears, at least in the Lau District, as a discontinuity. This discontinuity is marked by a thin even layer of phosphorite with glauconite. The sediments above and below this phosphorite layer are quite different. The Hemse Group is made up of a soft, grey marl with lenses and thin bands of limestone. Its uppremost part is finely sandy and frequently full of impressions of shells of a brachiopod, "*Strophomena*" *impressa*. The lower part of the Eke Group consists of a brownish-yellow, coarsely crystalline limestone, more or less well stratified. This limestone is composed chiefly of the calcareous parts of fossil invertebrates and algae. The colour seems to be due to small flakes of "limonite" (Goetite), which are abundant. The basal part of the limestone is a coarse conglomerate with pebbles up to 25 mm. in diameter. The pebbles are generally water-worn fossils, chiefly corals and calcareous algae, but some of them consist of more or less marly limestone with fragments of fossils. Thus, it is possible that some of the fossils mentioned earlier are from these pebbles, and consequently are older than the conglomerate. Real terrigenous material (insoluble in acetic acid) is practically absent in the coarser fractions (>0.02 mm); only some few grains of quartz were met with.

This type of rock is very common in the border-zones of the reef-limestones of Gotland, indicating a deposition in shallow water, where the action of the waves was strong, perhaps in the littoral zone of a coral-reef, the upper part of which was above or at least near the surface of the sea.

The age of the Eke Group is probably Middle Ludlowian. Unfortunately, our present knowledge of the fauna of the Eke Group does not permit of a direct and reliable determination of its relative age. It can only be placed between the well determined groups lying above and below it. Of these, the underlying Hemse Group is especially well determined, because of its relatively rich fauna of graptolites (HEDE 1942). It belongs to the Lower Ludlowian and corresponds to the zone of *Monograptus nilsoni* and, perhaps, also to the lower part of the zone of *M. scanicus*. One single specimen of *M. scanicus* has been found 12 m. below the top of the group (HEDE 1919).

Correlation table

Ösel	Gotland (chiefly Lau District)	Great Britain (type profile)		Scania
	Sundre Limestones Hamra	Downtonian Ludlow Bone-bed		Öved-Ramsåsa Group
K 4 ?	Burgsvik Group	Upper Ludlowian		
	Eke Group ? — — — ? — — —	Middle Ludlowian		
K 3	**Break** in the Lau District — — ? — — —	zone of: *Monograptus tumescens*	Lower Ludlowian	
		zone of: *M. scanicus*		Colonus Shale
K 2	Hemse Group	zone of: *M. nilsoni*		
	Klinteberg Limestone	zone of: *M. vulgaris*		
K 1	Mulde Marl	Wenlock		

The Burgsvik Group, directly superimposed on the Eke Group, is certainly of Upper Ludlowian age and contemporaneous with the upper Whitcliffe Flags (HEDE 1921; SÄVE-SÖDERBERGH 1941). The comparatively thin Eke Group thus represents a very great space of time (the whole Middle Ludlowian, and parts of Upper and Lower Ludlowian). As the sediments of the Eke Group do not indicate a slower rate of sedimentation than the Hemse and Burgsvik Goups, one may expect one or more breaks in the stratigraphical sequence here. This opinion is also supported by the occurrence of a well-marked surface of discontinuity, and a conglomerate between the Hemse and Eke Groups. This break is observed not only at Lau Backar and in Lau Kanal, but also at Nyudden, Maldes in När, and at some other localities (MUNTHE 1902).

Since some members of the Upper Ludlowian fauna (*inter alia Homalonotus knighti* and *Retzia bayley*) also occur in the Eke Group, it is likely that this group belongs to the upper part of the Middle Ludlowian, or even to the lower part of the Upper Ludlowian. Therefore the break may be expected chiefly to lie below the Eke Group, represented by the surface of discontinuity between the Eke and Hemse Groups.

If this suggestion is true, it means that the break here referred to, includes not only the zone of *Monograptus tumescens*, but also the greater part of the Middle Ludlowian, and perhaps even the upper part of the zone of *Monograptus* *scanicus.* Quite a number of local differences occur, however, and a detailed survey of the faunal and sediment-petrographical variations is necessary to solve this problem.

Of course, it is not the author's opinion that this break is common to the whole of Gotland; probably it is only a local phenomenon in the Lau District.

Another thing worth mentioning is that the layers above the Burgsvik Group, the Hamra and Sundre Groups, possibly belong to the basal Devonian (Downtonian). Now, most authors draw the boundary between the Silurian and the Devonian below the Ludlow Bone-bed, and then the uppermost layers of the Silurian will be the Upper Whitcliffe Flags, which are contemporaneous with the Burgsvik Group. Consequently the layers above the Burgsvik Group must belong to the Devonian.

The above stratigraphical table shows the suggested place of the break between the Hemse and Eke Groups. Most of the data are from Hede (1921, 1942) and Säve-Söderbergh (1941).

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Explanation of Plate I

Figs. 1–5. Coelolepid scales from Lau Backar. Middle (?) Ludlowian.
Fig. 1. Scale No. C. 1343. a) seen from above, b) seen from below. 50 x.
Fig. 2. Scale No. C. 1344. a) seen from below, b) seen from the side. 50 x.
Fig. 3. Scale No. C. 1345. a) seen from above, b) seen from below. 50 x.
Fig. 4. Scale No. C. 1346. a) seen from the side, b) seen from above. 50 x.
Fig. 5. Scale No. C. 1347. a) seen from below, b) seen from the side. 50 x.
Figs. 6–7. Acanthodian scales from Lau Backar. Middle (?) Ludlowian.
Fig. 6. Scale No. P. 4383. *Nostolepis-type.* a) seen from above, b) seen from below. 50 x.
Fig. 7. Scale No. P. 4384. *Gomphodus-type.* a) seen from the side, b) seen from below. 50 x.
Figs. 8–9. Indeterminable Cephalaspid from Grötlingbo. Upper Ludlowian.
Fig. 8. Specimen No. C. 1348. Whole specimen. Natural size.
Fig. 9. Same specimen. Frontal part of ventral rim. 4 x.

All specimens belong to the Swedish Museum of Natural History, Stockholm.

All specimens photographed by the author, and the photographs retouched by Mr. S. Ekblom.

Tryckt den 23 oktober 1950

Uppsala 1950. Almqvist & Wiksells Boktryckeri AB

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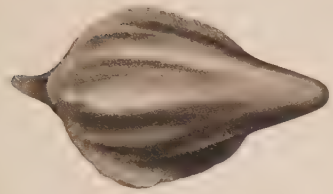

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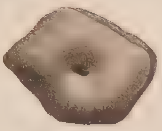

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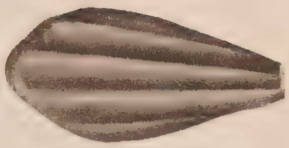

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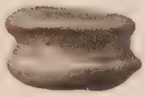

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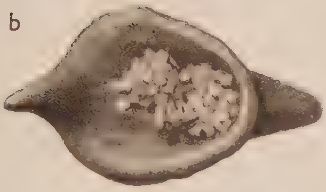

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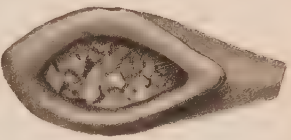

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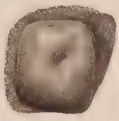

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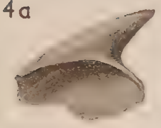

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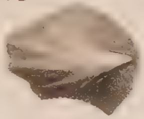

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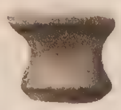

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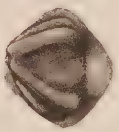

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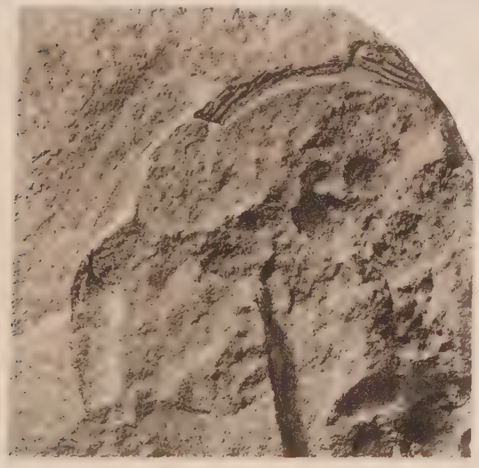

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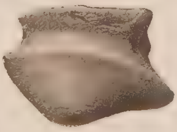

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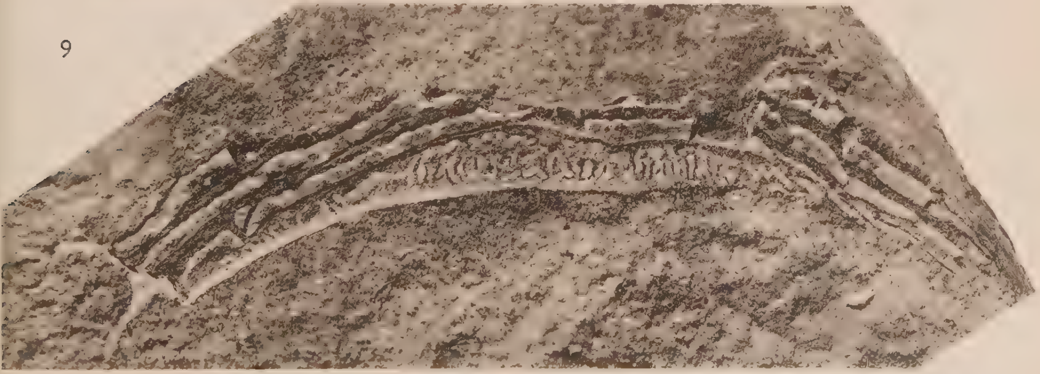

ARKIV FÖR MINERALOGI OCH GEOLOGI Band 1 nr 9

Communicated 11 October 1950 by ARNE WESTGREN

The crystal structure of galenobismutite, $PbBi_2S_4$

By FRANS E. WICKMAN

With 4 figures in the text

Introduction. The crystal structures of the sulpho-salt minerals are almost completely unknown. During the last decade M. A. PEACOCK and his co-workers in Toronto have determined the unit cells and space-groups of a large number of minerals belonging to this group. These investigations give us an indication of the most favourable cases for a structure determination, and are consequently most valuable.

One of these more favourable cases is galenobismutite, $PbBi_2S_4$ which was originally described from Nordmarken, Sweden, by HJ. SJÖGREN (1878). The X-ray crystallography was determined by L. G. BERRY (1940), who also reviewed the older litterature regarding this mineral.

Material. A very thin acicular crystal (0.05 mm thick) from the original locality (RMA yellow number 4030) was chosen for the present investigation.

Unit cell and space-group. Rotation and equi-inclination photographs were taken around the needle-axis (*b*-axis) using iron radiation. The cell dimensions found are in good agreement with those found by BERRY (Table I). The unit cell contains four molecules of $PbBi_2S_4$. As already shown by BERRY the possible space-groups are D_{2h}^{16}-*Pnma* or C_{2v}^{9}-*Pn2a*.

Atomic positions. This structure is dominated by the heavy atoms bismuth and lead which is an indication that it might be profitable to have a PATTERSON (010) projection. Such a projection is shown in Fig. 1, and it is characterized by its simple appearance, having except the origin only the five very strong peaks A–E.

Table I.

	BERRY (1940)	WICKMAN
a	11.72 ± 0.03	11.65 ± 0.05
b	4.07 ± 0.02	4.08 ± 0.03
c	14.52 ± 0.03	14.49 ± 0.05

A comparison with the structure of bismutinite showed that the projection could easily be described by a structure having the parameters (space-group *Pnma*)

4 X_1 in 4 (*c*)	$x_1 = 0.08$	$z_1 = 0.40$
4 X_2 in 4 (*c*)	$x_2 = 0.25$	$z_2 = 0.65$
4 X_3 in 4 (*c*)	$x_3 = 0.12$	$z_3 = 0.90$

where X_1, X_2, X_3 stand for bismuth and lead. These values were refined in the usual way. The sulphur atoms were located from space considerations using the values Pb–S = 2.96 Å, and Bi–S = 2.65 Å. The arrangement of the X_2 and X_3 atoms resembles very much the arrangement of the metal atoms in stibnite and bismutinite. This was taken as an indication that the sulphur atoms are arranged in a similar way, and so the position of the S III atom was easily found.

On the other hand it was possible to give the X_1 atom an octahedral coordination with sulphur atoms around it, and so this atom was identified as the lead atom.

The final parameters are:

Space-group: D_{2h}^{16}-*Pnma*

All atoms in 4 (*c*)	x	z
4 Pb	0.072	0.400
4 Bi I	0.250	0.645
4 Bi II	0.110	0.900
4 S I	0.333	0.035
4 S II	0.285	0.285
4 S III	0.077	0.090
4 S IV	0.013	0.735.

The agreement between calculated and observed F-values is satisfactory, if it is remembered that the absorption is rather strong for the smallest *h* and *l* values. (Tables II and III).

Discussion of the structure. The structure of galenobismutite is shown projected on (010) in Fig. 2. The interatomic distances are:

Kind of atom	Number of atoms	Kind of atoms	Distance
Pb	1, 2	S I, S I	2.96; 3.04
	1, 2	S II, S IV	2.98; 2.99
		Pb, Bi I, Bi II	3.92; 4.11; 4.24
Bi I	2, 2, 2	S I, S II, S III	2.77; 2.91; 2.98
	1, 1	S IV, S IV	3.07; 3.54
		Bi I, Bi II	6.60; 4.04
Bi II	1, 2	S I, S II	3.27; 2.91
	1, 2, 1	S III, S III, S IV	2.78; 2.99; 2.64
		Bi II	4.38

The sulphur atoms around the lead atom form a slightly deformed octahedron. The arrangements around the bismuth atoms are more irregular, but the six

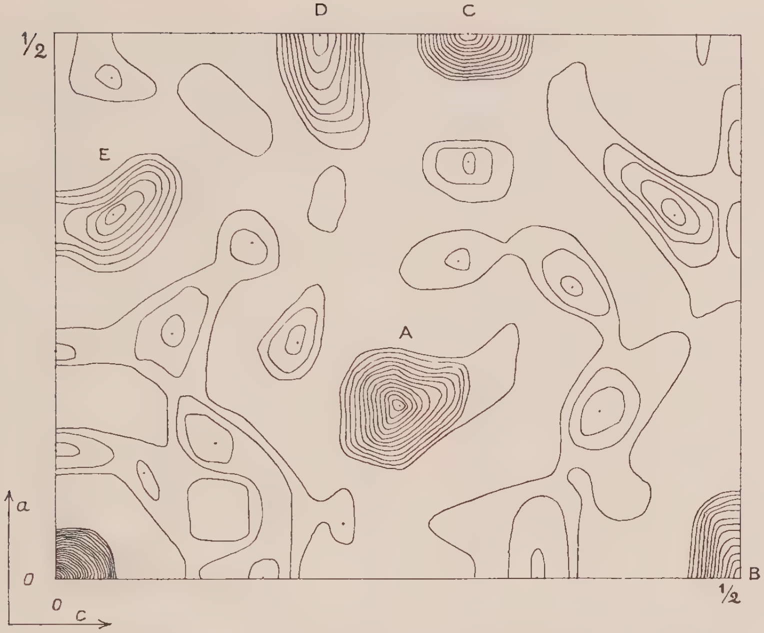

Fig. 1. A PATTERSON projection of galenobismutite on (010).

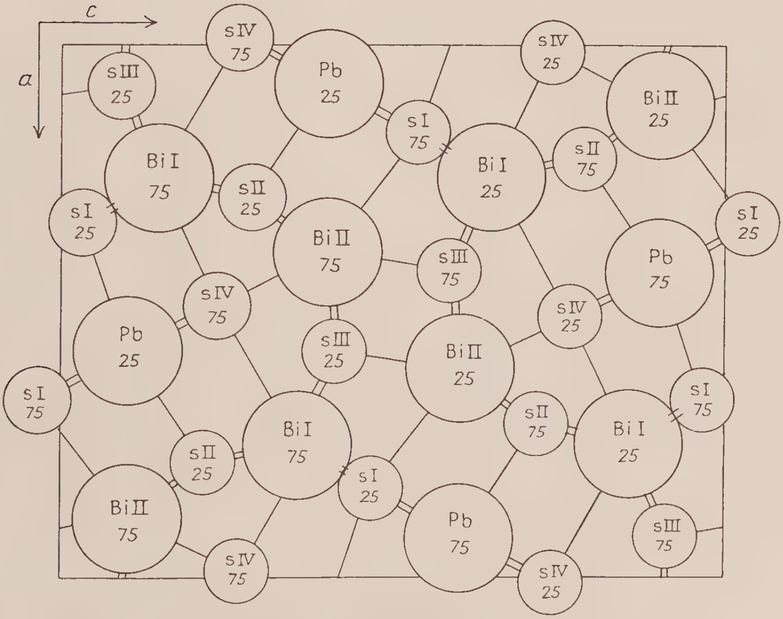

Fig. 2. The structure of galenobismutite, projected on (010).

Table II.

Weissenberg photograph of Galenobismutite. Rotation axis [010]. Zero layer line, Fe-radiation. Comparison between observed and calculated |F|-values.

h k l	|F| obs	|F| calc.	*h k l*	|F| obs	|F| calc.	*h k l*	|F| obs	|F| calc.
1 0 0	—	0	3 0 4	25	40	6 0 8	45	47
2 0 0	—	1	4 0 4	—	17	7 0 8	120	88
3 0 0	—	0	5 0 4	40	47	8 0 8	45	31
4 0 0	10	3	6 0 4	110	141	9 0 8	—	1
5 0 0	—	0	7 0 4	65	74	0 0 9	—	0
6 0 0	120	149	8 0 4	—	34	1 0 9	50	6
7 0 0	—	0	9 0 4	—	9	2 0 9	—	6
8 0 0	35	42	10 0 4	25	23	3 0 9	35	45
9 0 0	- -	0	0 0 5	—	0	4 0 9	20	25
10 0 0	35	5	1 0 5	5	6	5 0 9	—	14
11 0 0	—	0	2 0 5	20	9	6 0 9	45	42
0 0 1	—	0	3 0 5	35	39	7 0 9	50	33
1 0 1	—	5	4 0 5	15	11	8 0 9	40	13
2 0 1	—	13	5 0 5	20	28	9 0 9	65	57
3 0 1	—	30	6 0 5	—	3	0 0 10	75	71
4 0 1	20	37	7 0 5	55	68	1 0 10	—	15
5 0 1	30	28	8 0 5	—	9	2 0 10	100	94
6 0 1	45	34	9 0 5	70	72	3 0 10	—	15
7 0 1	30	48	10 0 5	—	4	4 0 10	90	115
8 0 1	30	4	0 0 6	55	82	5 0 10	50	7
9 0 1	95	59	1 0 6	—	8	6 0 10	30	40
10 0 1	50	46	2 0 6	105	100	7 0 10	—	5
0 0 2	—	21	3 0 6	115	122	8 0 10	75	58
1 0 2	—	1	4 0 6	120	94	0 0 11	—	0
2 0 2	—	31	5 0 6	—	38	1 0 11	55	10
3 0 2	115	182	6 0 6	30	30	2 0 11	20	13
4 0 2	50	65	7 0 6	25	15	3 0 11	—	25
5 0 2	15	35	8 0 6	50	38	4 0 11	70	28
6 0 2	—	14	9 0 6	65	50	5 0 11	40	14
7 0 2	—	2	10 0 6	80	63	6 0 11	35	32
8 0 2	50	29	0 0 7	—	0	0 0 12	—	25
9 0 2	115	90	1 0 7	5	0	1 0 12	95	96
10 0 2	30	10	2 0 7	—	1	2 0 12	30	33
0 0 3	—	0	3 0 7	25	24	3 0 12	30	39
1 0 3	—	2	4 0 7	40	31	4 0 12	—	21
2 0 3	—	4	5 0 7	30	7	5 0 12	90	71
3 0 3	20	32	6 0 7	75	65	6 0 12	20	26
4 0 3	40	51	7 0 7	30	2	0 0 13	—	0
5 0 3	—	0	8 0 7	30	10	1 0 13	45	2
6 0 3	75	87	9 0 7	—	25	2 0 13	25	3
7 0 3	25	15	10 0 7	70	85	3 0 13	15	4
8 0 3	45	1	0 0 8	50	73	4 0 13	—	29
9 0 3	—	22	1 0 8	115	127	0 0 14	35	32
10 0 3	60	71	2 0 8	40	10	1 0 14	35	17
0 0 4	45	163	3 0 8	20	37	2 0 14	70	81
1 0 4	40	59	4 0 8	—	17	3 0 14	65	49
2 0 4	—	12	5 0 8	75	61			

Table III.

Equi-inclination Weissenberg photograph of Galenobismutite. Rotation axis [010]. First layer line. Fe-radiation. Comparison between observed and calculated |F|-values.

h k l	|F| obs	|F| calc.	*h k l*	|F| obs	|F| calc.	*h k l*	|F| obs	|F| calc.
1 1 0	—	0	8 1 3	120	118	0 1 8	—	0
2 1 0	55	138	9 1 3	70	40	1 1 8	75	83
3 1 0	—	0	0 1 4	—	0	2 1 8	50	37
4 1 0	80	133	1 1 4	55	78	3 1 8	—	9
5 1 0	—	0	2 1 4	90	121	4 1 8	65	24
6 1 0	—	32	3 1 4	—	22	5 1 8	120	102
7 1 0	—	0	4 1 4	75	70	6 1 8	—	3
8 1 0	75	70	5 1 4	50	44	7 1 8	70	40
9 1 0	—	0	6 1 4	—	20	0 1 9	—	70
10 1 0	—	23	7 1 4	—	26	1 1 9	50	21
11 1 0	—	0	8 1 4	65	64	2 1 9	70	31
0 1 1	20	55	9 1 4	40	15	3 1 9	70	18
1 1 1	—	23	0 1 5	35	82	4 1 9	105	90
2 1 1	40	60	1 1 5	30	15	5 1 9	50	33
3 1 1	40	52	2 1 5	100	100	6 1 9	50	77
4 1 1	35	35	3 1 5	—	9	7 1 9	75	69
5 1 1	95	110	4 1 5	80	57	8 1 9	—	1
6 1 1	25	24	5 1 5	40	66	0 1 10	—	0
7 1 1	—	10	6 1 5	55	66	1 1 10	—	0
8 1 1	120	120	7 1 5	90	53	2 1 10	106	113
9 1 1	35	8	8 1 5	85	45	3 1 10	—	9
10 1 1	30	10	9 1 5	35	25	4 1 10	116	81
11 1 1	115	100	0 1 6	—	0	5 1 10	—	12
0 1 2	—	0	1 1 6	65	70	6 1 10	—	28
1 1 2	60	116	2 1 6	110	111	0 1 11	135	49
2 1 2	20	41	3 1 6	25	2	1 1 11	85	62
3 1 2	15	25	4 1 6	85	84	2 1 11	63	26
4 1 2	35	32	5 1 6	65	51	3 1 11	—	46
5 1 2	95	117	6 1 6	—	17	4 1 11	69	59
6 1 2	—	4	7 1 6	65	37	5 1 11	—	13
7 1 2	65	41	8 1 6	65	50	0 1 12	—	0
8 1 2	55	44	9 1 6	—	31	1 1 12	124	81
9 1 2	—	16	0 1 7	45	4	2 1 12	—	51
0 1 3	—	9	1 1 7	70	65	3 1 12	—	13
1 1 3	60	84	2 1 7	—	22	4 1 12	—	19
2 1 3	55	86	3 1 7	—	55	5 1 12	68	66
3 1 3	45	72	4 1 7	80	44	0 1 13	—	34
4 1 3	35	17	5 1 7	70	42	1 1 13	—	51
5 1 3	100	84	6 1 7	65	48	2 1 13	—	6
6 1 3	25	10	7 1 7	115	36	3 1 13	114	45
7 1 3	35	28	8 1 7	115	86	4 1 13	56	57

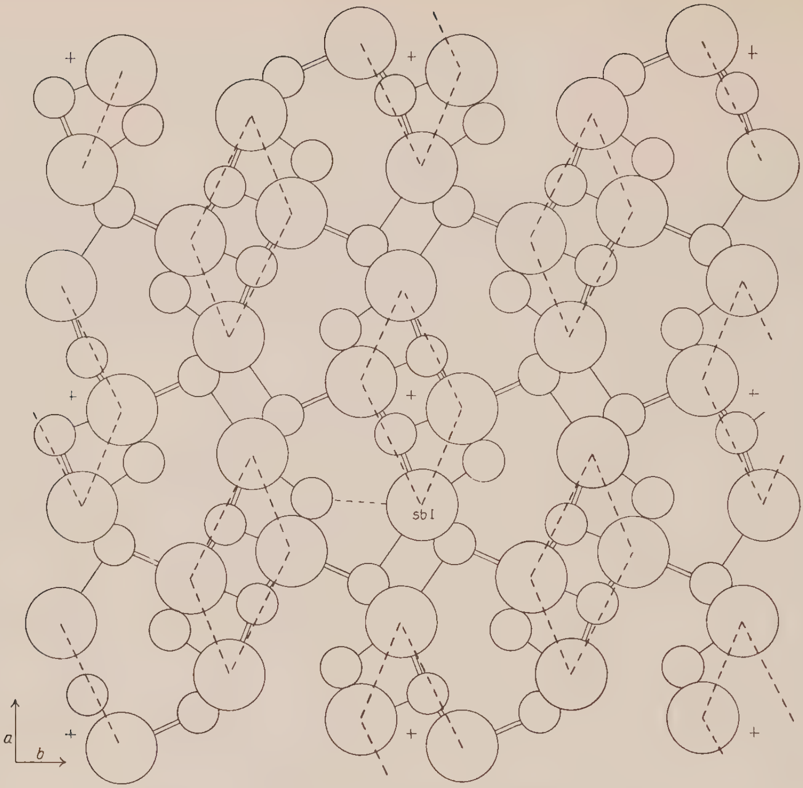

Fig. 3. The structure of stibnite, projected on (001).

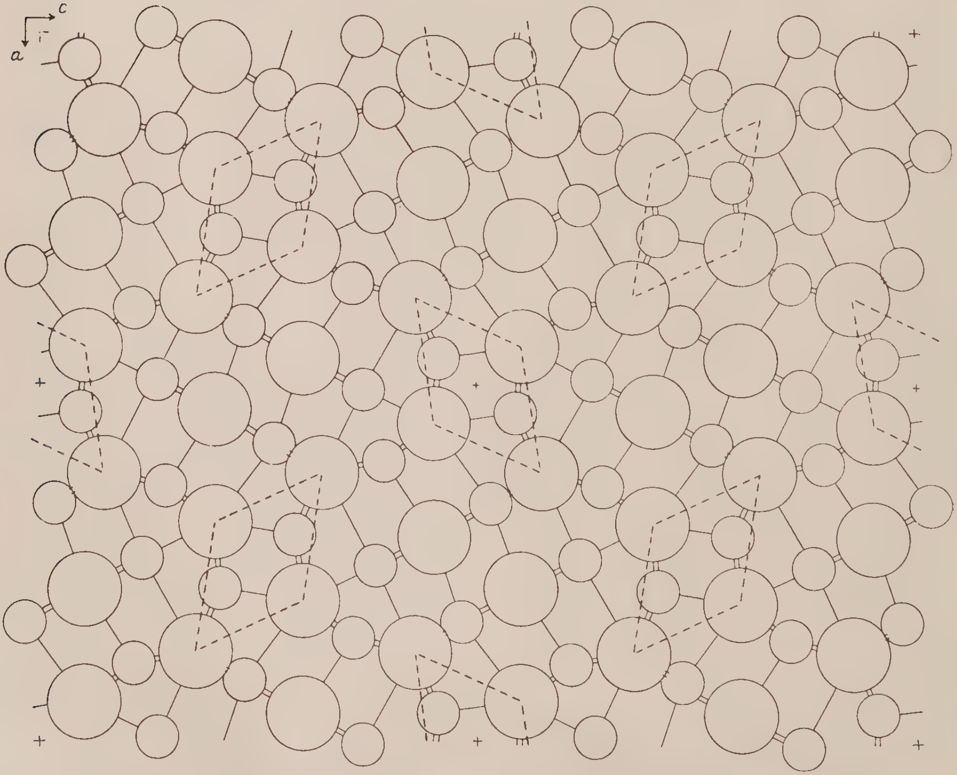

Fig. 4. The structure of galenobismutite, projected on (010) to show the chains and their linking.

closest sulphur atoms around Bi I form a trigonal prism. The arrangement around the Bi II atom is very similar to that around the SbI atom in stibnite (W. HOFMANN 1933). The lead and bismuth atoms around the S I atom form a distorted octahedron. Around the other sulphur atoms we have more irregular five coordination.

A comparison between the double chains in stibnite (Fig. 3) and galenobismutite (Fig. 4) shows that we have crosslinking in galenobismutite.

A more complete discussion of the structure of galenobismutite will be given in connection with a paper discussing the crystal chemistry of other acicular sulpho-salt minerals.

Acknowledgements. The present investigation has been supported by a grant from the Swedish Natural Science Research Council.

Riksmuseets Mineralogiska Avdelning, August 1950.

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Uppsala 1951. Almqvist & Wiksells Boktryckeri AB

ARKIV FÖR MINERALOGI OCH GEOLOGI Band 1 nr 10

Read 22 November 1950

The Charnockite series of the Varberg district on the south-western coast of Sweden

By Percy Quensel

With 6 plates and 37 figures in the text

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Introduction

A casual visit to Varberg, on the west coast of Sweden, in the summer of 1945, presented me with the opportunity of examining superficially some exposures of the so-called 'Varberg granite', a rock complex long known, both in appearance as well as in mineralogical composition, to hold an exceptional position in relation to the Swedish archaean rocks in general.

As early as 1880 A. E. TÖRNEBOHM concludes a short description of the Varberg rocks with the following words: "In respect of their mineral composition, the rocks in question are exceedingly remarkable and are deserving of a more detailed description".[1] In 1893 E. SVEDMARK, while mapping the district for the Geological Survey, also called attention to the singular appearance of the 'Varberg granite' and indicated its approximate distribution by means of a special marking on the Survey sheet. In the description to the map he remarks: "As regards colour and general aspect, this singular rock is without counterpart in Sweden".[2]

On account of its unusual character, specimens of the Varberg rocks have long been represented in petrographical collections, both at home and abroad. A contributary cause has been that, since the middle of the nineteenth century, the rocks in question have been rather extensively quarried for building and road-making material. A great number of larger and smaller quarries have therefore made good specimens easily obtainable.

Although as long as 70 years ago attention was called to the Varberg rocks as calling for a more detailed investigation, no further research work was carried out. In private discussions, however, different opinions have been advanced regarding the petrological relationship between the Varberg complex and the surrounding gneiss formation. On this account I had, for some time, wished to see if one could detect in the field any features throwing light on the petrological problems presented by this area.

Although, on my first visit in 1945, I only had a few hours between trains at my disposal, I could observe on some sea-washed flags on the coast certain indications which seemed to suggest positive conclusions as to a definite petrological sequence between the rock formations involved. I therefore made a point of returning the following summer for the purpose of making a more detailed survey. A fortnight in the field in 1946 yielded so many unexpected observations of interest — but at the same time problematic of interpretation — that further work was found necessary, and it was continued in 1947 and 1948.

A detailed survey in the field as well as chemical and microscopical investigations have led to the conclusion that the rocks of the Varberg district represent a petrological complex of varying composition, closely related to the charnockite series, as they were first designated by Sir Thomas Holland in his description from Peninsular India.

The name "Varberg granite" is erroneous. The rock types to which this name has been assigned, contain very little or no quartz and would, following a normal classification of igneous rocks, most closely correspond to different sub-species of monzonites and pyroxene-syenites.

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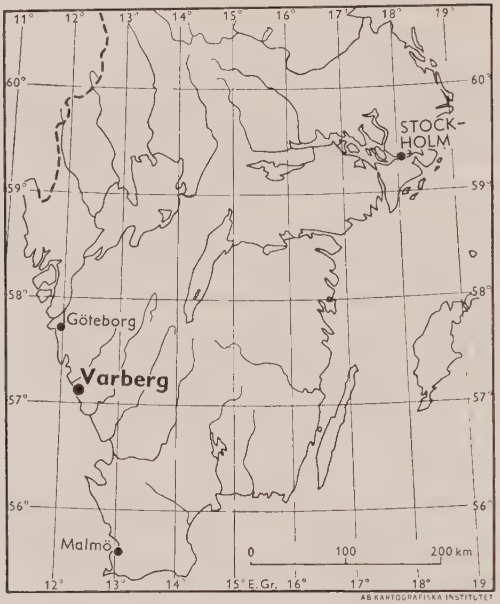
[1] Geol. För. Förh. V, 1880, p. 20. (Original Swedish text: till sin mineralogiska sammansättning är ifrågavarande bergart särdeles märklig och förtjänar en närmare beskrifning.)

[2] Sveriges Geol. Undersökning, Ser. Ab, nr 13, 1893, p. 22.



AB KARTOGRAFISKA INSTITUTET

Fig. 1. Location of the Varberg field.

Application of the names 'charnockite' and 'charnockite series'

Before dealing with the petrology of the Varberg rocks and discussing their relationship with other rocks of the charnockite series, it will be appropriate to define the terms charnockite and charnockite series as applied in this paper.

In almost every treatise dealing with rocks presumed to belong to this group, a beginning is made by citing HOLLAND's original definition of the terms charnockite and charnockite series. As regards their use in this paper, I feel it necessary to do the same, as in many cases the names have been given a wider application than Holland anticipated.

On page 125 of his memoir on "The Charnockite Series, a group of Archaean hypersthenic rocks of Peninsular India" Holland says, "the one constant feature in the structure is the even-grained, granulitic character of the constituents".

On page 130 he continues: "Whilst, therefore, we group together, and map as one formation, a number of diverse varieties of rocks (which are true compatriots within this petrographical province) under the name 'charnockite series' the various constituents of this formation may be distinguished from one another by the ordinary names used for equivalent mineralogical aggregates". On the following page Holland writes: "Unless a similar formation, found in another country, can be proved to be a genetic relation of the typical exposures described in this paper, it is hoped that the name 'charnockite' will never be used outside India. The name is applied to a definite member of a very definite petrographical province now exposed in India, and unless outsiders give it a wider application than now proposed, the terms 'charnockite' and 'charnockite series' need never become a burden to petrographical nomenclature. Charnockite is a convenient name for a quartz-felspar-hypersthene-iron-ore rock in the charnockite series and is not a name for any hypersthene granite occurring in other petrographical provinces". (Holland p. 125—130).

I have quoted Holland in order to establish his very precise definition of the terms 'charnockite' and 'charnockite series', and to emphasize his so positively expressed wish that these names should not be used in any other sense. However, this wish has not always been observed; in several instances the names have been given a less restricted meaning than Holland desired. As an extreme example I may cite GEVERS and DUNNE, who, in their paper on "the Charnockitic rocks near Port Edward in Alfred County, Natal" write the following introductory note: "In general petrographical nomenclature of today the name charnockite is being used more or less for any hypersthene granite". (Gevers and Dunne, p. 183). If this should become general, the names charnockite and charnockite series would lose their petrological individuality as representing a very definite rock assembly within ancient archaean formations.

In a rather extensive collection of charnockitic rocks from different continents, which, thanks to the ready courtesy of friends and of co-workers on the charnockitic problem, have come into my possession, I have again and again been surprised at the very uniform exterior appearance of the rocks, from wherever they originate. Exceptions to this rule are in every instance found to involve rocks not strictly tallying with Holland's definition and description of the charnockite series.

As the rocks of the Varberg district exhibit in nearly every detail Holland's distinguishing features of the charnockite series, I have not hesitated to use his nomenclature. In colour and fracture, in the fresh aspect of the rocks, in the xenomorphic granular texture, in the occurrence of divisions of different chemical composition, as well as in general mineral composition, a singularly close relationship to Holland's type rocks is obvious. The mineral association is also found in detail to be representative of the charnockite series, wherever they occur in typical development. This includes the abundant occurrence of antiperthite, a marked tendency for the plagioclase to occur without twinning lamellae, a general combination of monoclinic and orthorhombic pyroxenes and the presence of garnet in varying amounts in different types of the rock series.

In one instance a departure will be made from Holland's nomenclature. The name charnockite was restricted by Holland to the acid charnockites, the more basic types being styled the intermediate and basic divisions of the charnockite series. This somewhat cumbersome designation has already been disregarded by most of the Indian geologists who have more recently been working in the charnockitic rocks of the Peninsula. They have instead used the names basic charnockites, intermediate charnockites, sub-acid and acid charnockites, all belonging to the collective name the charnockite series.[1] This nomenclature will be followed here as being more explicit. The restriction of the name charnockite to the acid division of the charnockite series would in any case now lead to misinterpretations, since the name acid charnockite has already come into common use.[2]

The term charnockite series is used here as a collective designation of the whole assemblage of charnockitic rocks.

One other question of terminology in Holland's paper is in need of further explanation. Holland states that "the one constant feature in the structure is the even-grained granulitic character of the constituents", and this has apparently been a feature of important significance in characterising the rocks of the charnockite series. However, after the words "even-grained granulitic" Holland adds within parenthesis the term "panidiomorphic". This must be either a misunderstanding or a miswriting of the term, as becomes obvious from the subsequent descriptions of the rocks of his charnockite series. I may quote a typical instance, where he discusses the basic division of the charnockite series from the original locality: "the norites are almost always granulitic (panidiomorphic) in structure, neither the ferro-magnesian silicates nor the plagioclase showing any noticeable approach in idiomorphic outlines" (Holland, p. 154). The contradiction is evident: first the rocks are said to be panidiomorphic in texture, and then in the same sentence it is said that none of the minerals show any noticeable approach to idiomorphic outlines.

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[1] cf. Rama Rao, 1945, p. 162.

[2] I am aware that this is not in accordance with the recommendation made by the Committee on British petrographic nomenclature. (Min. Mag. Vol. 19, 1920, p. 139).

I should not have dwelt on this misinterpretation of the term 'panidiomorphic' if it had not led to further misunderstandings in quotations of Holland's apprehension of the textural development of the charnockites. So, for example, when Gevers and Dunne write under the heading Texture: "Holland not only emphasized the constancy in mineral composition of the normal rocks of his charnockitic series, but also a constancy in structure and texture. In stressing the even-grained granulitic character of the mineral constituents, Holland, however, followed the French usage of the term 'granulitic', meaning panidiomorphic granitic". (Gevers and Dunne, p. 192). The French term "structure granulitique" was defined by MICHEL LÉVY as follows: "Une structure cristalline grenue avec éléments automorphes, notablement le quarz". (Michel Lévy, 1879, cf. Lexique pétrographique, Compte Rendu, VIII Congrès Géologique International, Paris 1900, p. 1117). I do not know on what grounds Gevers and Dunne so positively state that Holland followed the French usage of the term "structure granulitique". Holland himself gives no indication. It may have originated from HOLMES Nomenclature of Petrology, where, under the heading "Granulitic Structure", it is rightly observed: "In France the same term has also been used as synonymous with panidiomorphic-granitic texture". This is, however, just what Holland does not want to indicate, as is clearly manifested by his own words (see above). The only explanation must be that Holland confused the distinction between idiomorphic and allotriomorphic in the original sense of these terms. The explanation may be found in an odd coincidence. In ROSENBUSCH's Elemente der Gesteinslehre an erroneous wording has crept in which was only amended in the fourth edition. A. JOHANNSEN observed on this point: "Rosenbusch used the term panidiomorphic-granular for the texture of aplites. (Elemente der Gesteinslehre, 3. edition, p. 262). A rock of the appearance of aplite is as far as possible from panidiomorphic. In the latest edition of Rosenbusch's Elemente (p. 294) OSANN properly describes aplite as pan-allotriomorphic-granular". (Johannsen, I, p. 39).

In this paper the term 'xenomorphic granular texture' will be used. By xenomorphic is indicated — following Johannsen's definition of the term — that the constituents have crystallised more or less simultaneously, but have interfered with each other's growth to a greater degree. (Johannsen I, p. 39). By the added term 'granular' I indicate "a texture due to the aggregation of minerals of approximately equal size, whether in clastic, igneous or recrystallised rocks", as originally defined by CROSS (Holmes, Nomenclature of Petrology, p. 111). These references have been made to define more precisely the texture of the charnockitic rocks of the Varberg district than does the commonly used term "granulitic texture" indicate.

The more or less banded structure in many rocks of the Varberg series may be termed "granulose structure" defined by Holmes as "a structure characteristically developed in granulites, due to the presence of granular minerals, such as quartz, felspars, garnets and pyroxenes in alternating streaks and bands, developed on a megascopic or microscopic scale. Successive layers may differ in colour, texture or mineral composition, but typical foliation is absent". (Holmes, p. 112). In the sense intended above, the terms 'xenomorphic granular texture' and in some instances 'granulose structure' fully cover the textural and structural development in the charnockitic rocks of the Varberg district.

In the following pages reference is in many cases made to charnockitic rocks from other regions. I have, however, restricted myself to such occurrences as can be presumed to represent the most typical rocks appertaining to the charnockites and charnockite series, as defined by Holland in his classic memoir. This does not imply that many of the papers mentioned in the appended bibliography, though not referred to in my text, may not include descriptions of truly charnockitic rocks. When, however, the descriptions are based only on casual specimens, often collected by non-initiated explorers, who do not give any reliable field data, or when the kinship with the charnockites has been based only on chemical similarities, the petrological position of the rocks in question have for the present been left open. They have, therefore, not been taken into consideration in that connection. In some cases certain rock assemblages, previously taken as representative of charnockitic rocks, have been discarded, since many petrological features in their setting were not found to be in accordance with the presumed metamorphic evolution of the charnockitic rocks. The reasons will be given under a subsequent heading.

Distribution and mode of occurrence

The area, within which the charnockite rocks of the Varberg district are found, forms part of the extensive gneiss formation of south-western Sweden. In the neighbourhood of Varberg this rock formation is of uniform development, in the form of a light red gneiss with a mottled appearance, due to large clusters of dark quartz and biotite or hornblende irregularly distributed throughout the rock. Generally the texture is xenomorphic, at least as regards the quartz-felspar components. One can, however, often discern a tendency of the felspars to develop porphyroblasts, the rock then grading into an augen-gneiss. In other parts the gneiss may become rich in garnets. On his map of the district Svedmark has indicated some such regions as augen-gneiss and garnetiferous gneiss.

The gneiss around Varberg is in general rich in magnetite, which has been noted as a characteristic feature of the whole complex of gneissose rocks of south-western Sweden. On this account, the name 'the iron-gneiss formation' (järngneisformationen) has from of old been given to the whole of the extensive region.

Within the gneiss area more basic rocks are of frequent occurrence. They may in general be classified as rocks of gabbroic composition in various stages of progressive uralitisation and amphibolitisation. On his map Svedmark has collectively designated them schistose diorite and diallage-amphibolite.

True amphibolites also occur in the district round Varberg, mostly in the form of dyke-like bodies or lenticular masses, interlayered within the gneiss complex.

The charnockitic rocks of the Varberg district are surrounded on all sides by the gneiss formation, which has been assigned to the so-called Gothic period of the

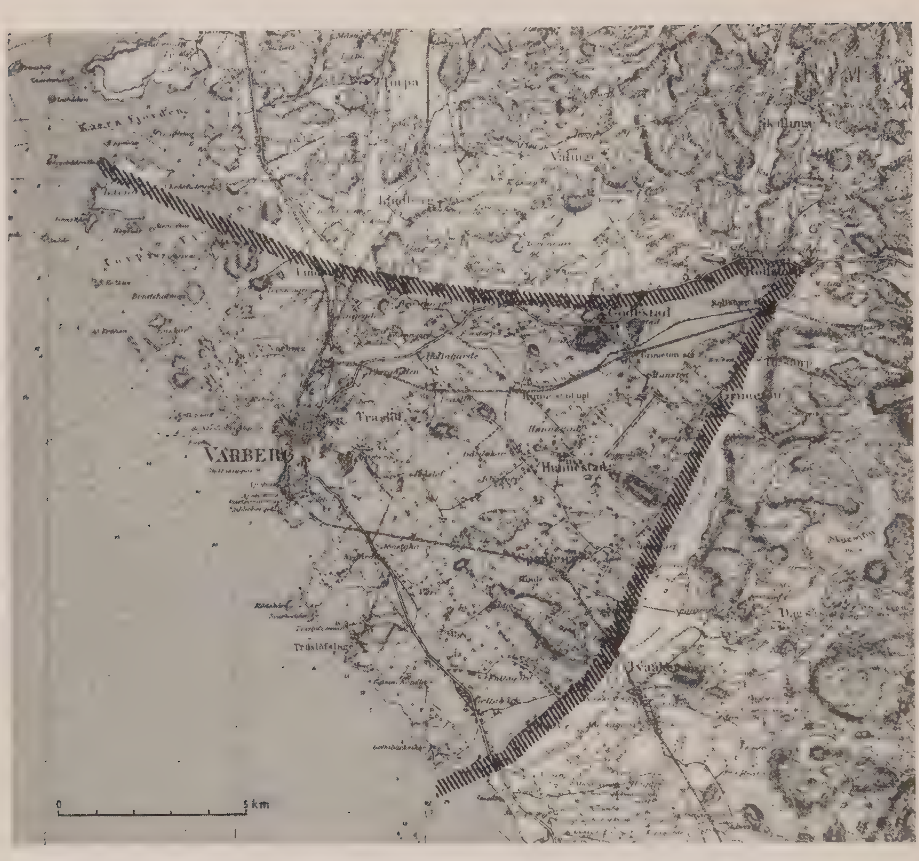

Fig. 2. Approximate boundary of the charnockitic area.

Swedish archaean. This is not now considered to represent the oldest division of the archaean rocks in Sweden, but instead the part which has probably been subjected to the most intensive deep-seated metamorphism.

The extension of the charnockitic rocks covers in a general way a triangular area, with one side facing the Kattegat. (Fig. 2.) The extension is approximately 150 square km. Only in some places outside this area, have small isolated occurrences been observed, as for instance at Öströö, about 5 km from the triangular boundary.[1]

The specific rocks of the charnockite series in the Varberg district, most typically represented by basic, intermediate and sub-acid types, generally occur as distinctly bounded massifs, on all sides surrounded by a fine-grained aplitic granite.

The dark-coloured basic charnockites are less in quantity but occur spread out over many localities, principally on or near the coastal part of the charnockitic area. The principal localities are in the vicinity of the fishing village of Träslövsläge and at Spannarp and in a larger mass at Gödestad. More isolated occurrences are found

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[1] This occurrence is not colour-marked on the map, as the intervening ground is soil-covered and the field connections with the mapped area thus obliterated.

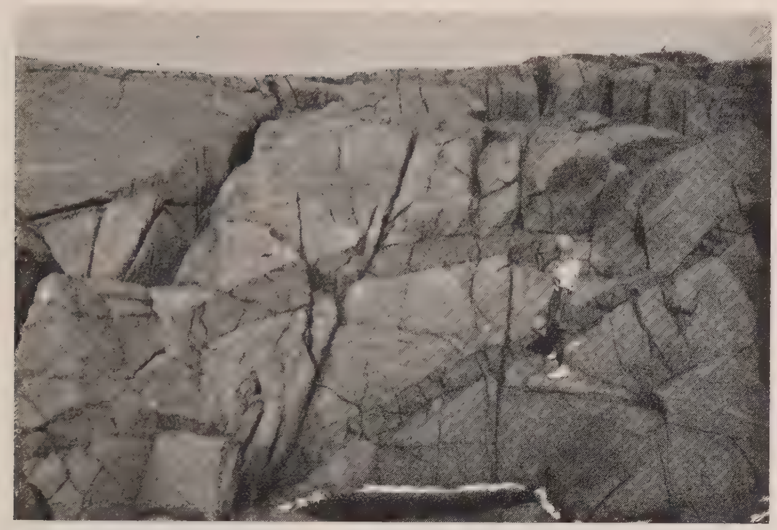

Fig. 3. Dyke-like exposures of basic charnockite in intermediate charnockite. Island of Sadeln.

in a railway-cutting at Lassabacka[1], E of Ekregården and S of Klastorp. Other outcrops will be mentioned in the following petrographic description. Especially at Träslövsläge, Spannarp and on the small island of Sadeln the exposures show a marked NW and WNW elongation and tend to have a dyke-like appearance (Plate VI and Fig. 3). Where contacts with the adjoining rocks are observable, in this case generally with the aplitic granite, more seldom with the intermediate charnockite, the rocks are generally sharply delineated.

The intermediate charnockites are the most common types of the specific charnockite series of the Varberg district. They occur in larger accumulated masses than the basic types and are more uniformly distributed over the whole area, though to a certain degree they also show a tendency to concentration towards the coastal regions. The fact that the normally developed intermediate types have been extensively quarried has contributed to many good exposures.

A large quarry near the beach, just south of the old fort of Varberg, affords a very good general view of the varying structural development of the intermediate charnockites.

Some types which will be designated below (p. 237) as the felsic charnockites of the Varberg series are principally found in the southern part of the district around Träslövsläge and Himle railway-station. These occurrences are about 15 km apart, but the intervening land is soil-covered, so that no connection can be established.

Finally there remains to be mentioned the aplitic granite, which in its field distribution is found to be intimately connected with the charnockitic rocks. Its distribution is bounded by the surrounding gneiss formation in the same way as in the case of the more specific charnockites. It is developed very uniformly throughout as a fine-grained felsic rock of a light red colour. If, in its local distribution, it were not so closely connected with the charnockitic rocks and there so intimately intermixed with them, I should hesitate to associate this aplitic granite with the charnockite series, since very similar aplitic granites occur widely distributed throughout the archaean formations of Sweden. Though the aplitic granite is in no way petrographically related to the charnockitic rocks, all observations in the field nevertheless seem to indicate that it must in some respect be genetically associated with the rocks of the charnockite series through a co-metamorphic deep-seated transformation. This problem will be dealt with in further detail under a later heading (p. 312 and 314).

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[1] The name Lassabacka is not entered on the topographical map of the Varberg district. The locality is situated at the second railway bifurcation, 2 km north of Varberg town.

As seen from the map, the aplitic granite is the quantitatively prevalent rock within the charnockitic area of the Varberg district. Over large areas it is completely predominant.

Descriptive account of the charnockitic series of the Varberg district

1. Characteristic features of the rocks in general

Both in general appearance and in the variations of different types from basic to intermediate and sub-acid composition, the Varberg rocks exhibit most of the features which have been emphasized as being characteristic of the charnockite series. In general they show a definite brownish weathering, which facilitates their identification in the field.

The colour of the different types is in full accordance with what has been noticed as characteristic of the original occurrences in India as well as of the typical charnockitic rocks of Equatorial Africa. The basic types are dark gray to black, naturally due to an excess of mafic minerals. The intermediate types vary from grayish-green to grayish-blue or brownish gray. In some sub-acid varieties a more distinct blue colouring prevails. On the whole the felsic charnockites correspond in colour to the intermediate division, but are generally of a somewhat lighter shade.

It is evident that in the intermediate rocks of the Varberg area, as in most of the typical intermediate rocks of the charnockite series, the characteristic colouring in greenish and brownish shades is due to the colouring of the felspars and not to the mafic minerals. This gives the rocks a darker colour than would be expected from their mineral composition. A positive proof of this is that an almost purely felspathic rock from a pegmatitoid segregation, practically free of ferro-magnesian minerals, exhibits the same brownish colour as an adjacent rock of normal intermediate composition. As free quartz is not present in the rock analysed (Niggli value qz —4.3) the brownish colour of the rock can only be occasioned by the brownish colour of the felspars.

The usual brownish or brownish-gray colouring of the felspars in the charnockitic rocks has generally been ascribed to minute dust-like inclusions. It has been difficult to ascertain their nature on account of their sub-microscopic dimensions, but different authors have assumed them to be biotite[1] or rutile.[2] The felspars of the Varberg charnockites show no indications of any such dust-like inclusions. The turbid colouring is instead probably due to a sub-microscopic intergrowth of two felspars. Tilley has already suggested such an explanation.[3]

In outward appearance the structure of the rocks is by no means uniform. The dark rocks of the basic division are always quite massive with a fine-grained equigranular fabric. Though having fractural planes, well observable where they are quarried for road material, they are extremely hard to cleave in smaller fragments.

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[1] Groves, p. 154. [2] Rama Rao 1945, p. 13. [3] Tilley, BANZ, p. 9.

The intermediate types, on the other hand, are variable in structure. In one and the same quarry there may occur completely massive rocks, while close by the same rock type may be distinctly laminated (granulose). This is therefore not the result of any subsequent dynamo-metamorphism or other compressional stress, but must be attributed to a syn-metamorphic flow structure. The lamination is due to a tendency of the mafic minerals to occur in linear arrangement.

A singular development is to be seen in a wholly deviating type. This rock is very fine-grained and has an outward appearance more like a dark quartzite than a rock of the charnockite series. In the most fine-grained specimens no minerals can be detected without a lens. The colour is bluish-black with an almost vitreous lustre. It may be of interest to note that WASHINGTON describes an evidently very similar development in rocks from Holland's type locality at Magazine Hill, St. Thomas Mt. in Madras. His description runs thus: "It is very fine-grained, looking much like a dense quartzite, of a dark, somewhat greenish, brownish-gray colour and a vitreous, almost greasy lustre" (Washington, p. 324). This description might equally well be used for the Varberg type of rock, which in outward appearance is evidently very similar, though darker in colour.

Assuming an approximate SiO_2 percentage in an analysis, as for example over 65% (JENS BUGGE, 1943, p. 61) as a dividing line for the acid charnockites, no typical rocks representing this division can be said to occur within the Varberg area.

In many papers the name 'granulite' has been used with somewhat varying signification for rocks which, in the field, have been found to be more or less closely connected with true charnockites (cf. p. 304 and following). In outward appearance and structural development they can have much in common with adjacent rocks of the charnockite series. In mineral composition, however, essential differences are manifested, inasmuch as pyroxene minerals are either absent or only casually present, and other mafic minerals only occur in insignificant amounts. A syngenetic relationship between such granulites and the specific charnockites has generally been presumed on account of difficulties in distinguishing the rocks from each other in the field.

Rocks corresponding in many details to these so-called granulites of other charnockitic regions are of frequent occurrence in the Varberg district. I have, however, hesitated to use the name 'granulite' for the rocks in question, since in petrographical literature the term has been given a wider application. Also the banded structure of most granulites from their typical localities is not a significant feature of the Varberg rocks. I have instead chosen to name these rocks *felsic charnockites*. This name would then signify such members of the charnockitic series as are devoid of mafic minerals or in which such minerals are only sporadically present in trifling quantities. Within the Varberg area felsic charnockites, in all probability corresponding to the so called 'granulites' of other charnockitic regions, are found in the field to grade into adjacent intermediate charnockites or into the aplitic granite without any observable demarcation.

Finally it remains to mention the aplitic granite within the area of the charnockite rocks of Varberg. As already mentioned, it is a fine-grained rock, light red to pink in colour and almost devoid of mafic minerals. Within the wide area over which it is distributed, in many cases without intervention of the other rocks, it is of so uniform a development that there is little to add regarding its general features.

In several places, however, the aplitic granite is found intimately intermixed with intermediate or felsic charnockites, resulting in the formation of typical hybrid rocks. In and around the little fishing village of Träslövsläge such assimilation phenomena and hybridism can well be followed in detail in many of the small quarries, where every transition is to be seen from more or less assimilated xenoliths of the pink granite in the greenish charnockitic rocks to streaks or faded remnants of charnockitic rocks in the granite.

2. Characteristic minerals of the Varberg charnockite series

The most characteristic minerals and their specific development in the charnockite rocks of the Varberg district, especially in view of their non-existence in the surrounding archaean formation, are the persistent antiperthitic texture of the felspars, the habitual absence of the albite twinning in the plagioclase and the presence of an orthorhombic pyroxene in most of the typical charnockite rocks. Garnet may also be said to represent a characteristic mineral, since it is present in most of the rocks belonging to the series.

The antiperthitic development of the felspars has of late been emphasized as a very characteristic feature of most rocks of charnockitic origin. In the Varberg series it is met with in most of the rocks of basic, intermediate and sub-acid composition and in many cases represents the predominant development of the felspars. In some of the basic rocks, the whole content of potassic felspar is found only in antiperthitic intergrowth in the form of irregular blebs or of more or less orientated lamellae.

Another peculiarity of the felspars is the tendency of the plagioclase to be free from normal albite twinning. When twinning does occur, it is in many cases so finely laminated as only to be observable under high magnification in favourable positions. Orthoclase is the prevailing potassic felspar. Microcline is found only in the aplitic granite, in contaminated rocks near the contacts with the surrounding gneiss, in xenoliths of gneiss within the charnockitic area, and to a certain extent in some of the felsic charnockites.

The most characteristic mineral of the charnockitic series has always been considered to be hypersthene or, to use a more general term, an orthorhombic pyroxene. In the Varberg series hypersthene is found in most of the different types in varying amounts. It is nearly always accompanied by a monoclinic pyroxene, but the proportions between the two pyroxenes are subject to considerable variation. This can in certain cases go so far that only the one or the other of the pyroxenes is present.

The hypersthene has many of the characteristic features which have been observed from other occurrences of the charnockite series. The pleochroism is variable. The strongest colour of absorption is, however, found to be very constant in the hypersthene of the basic charnockites. At the same time its precise colouring is difficult to define with precision. One finds the most varied terms used for what probably represents much the same colour of the strongly pleochroic hypersthenes in charnockitic rocks, such as pink, flesh-pink, hyacinth-red, claret-red, and so on. As it is difficult to grasp the precise meaning of these colour designations I have preferred to define the colour as light purple-violet according to RADDE's "Internationale Farben-Skala" Nr. 24, s—t, which colour exactly corresponds to the strongest absorption of the hypersthenes in the basic charnockites in question. In the intermediate types the hypersthene often shows a much weaker pleochroism in the direction of the strongest absorption, then merely reaching a pale pink colour or being practically non-pleochroic.

The strongly pleochroic hypersthenes sometimes exhibit an anomalous oblique extinction. This phenomenon has been recorded from other charnockitic regions. The cause has been discussed by many authors and explained by the non-development of the usual prismatic cleavages, the extinction angles having been measured against partings // (010) (WASHINGTON, p. 331) or against pyramidal faces (NAIDU, p. 157, JOHANSEN, p. 212, GUPTA, p. 123).

The diopside is light green in colour throughout and is only at times very faintly pleochroic.

Optical determinations of the two pyroxenes will be given in connection with the petrographic description of the different rocks.

Especially in the basic charnockites the garnets have colours closely resembling the strongest absorption colour of the hypersthenes. The colour of the two minerals can then in many cases be practically identical, as Holland has also noted in the case of the charnockitic rocks from Madras (Holland, p. 160).

All the rocks of the charnockite series in the Varberg district are rich in ore minerals. During a temporary visit to Stockholm, Professor RAMDOHR has kindly made a detailed examination of the opaque minerals in charnockites from different occurrences within the area. For the result I refer to Ramdohr's own report (see appendix I). It may only be observed here that the minerals in question are often of a complex nature, taking the form of intergrowths and disintegrations between the different components. They have been found to include magnetite, titanomagnetite, ilmenite and haematite-ilmenite, as well as pyrrhotite, chalcopyrite, pentlandite, sphalerite and both primary and secondary pyrite.

Petrographic description

1. The basic charnockites

(The former basic division of the charnockite series.)

The basic charnockites of the Varberg district may be separated into several sub-divisions on the basis of the hornblende content. The types wholly free of hornblende, or containing only some insignificant flakes of the same, may be considered to be the most representative specimens of this series from the point of view of metamorphic transformation. Exposures of this type are found rather sparsely distributed within the area. The best localities are found at Träslövsläge, at Klastorp, at a railway crossing at Lassabacka, and in a more considerable mass at Gödestad.

In all these localities the rocks have much the same textural development and mineral composition. They are all massive, fine-grained and almost black in colour, and the texture is xenomorphic granular throughout (Fig. 4). The characteristic mineral association is represented by felspars, diopside, hypersthene, garnet and ore minerals.

Within the felspar group, plagioclase predominates completely over potassic felspar. Its composition is singularly constant between an acid andesine and a basic oligoclase (about Ab 65, An 35). With respect to the basic composition of the rocks (44.60%, SiO_2, for example, in the analysed specimen from Lassabacka) one

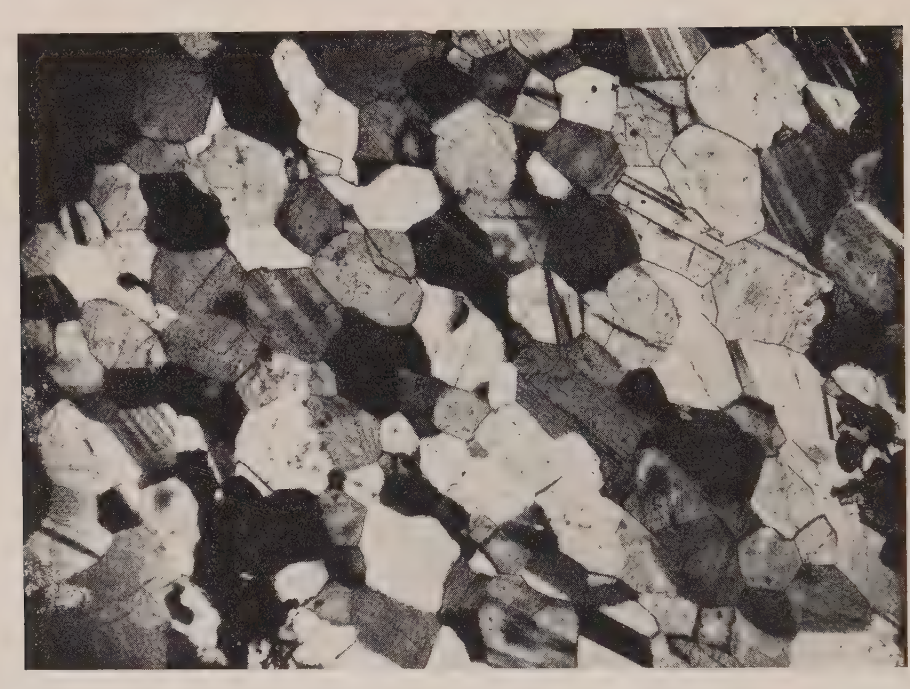

Fig. 4. Xenomorphic granular texture in a granulose leucocratic band of basic charnockite. ×9. Gödestad, ENE of Varberg.

would not expect so acid a plagioclase. The explanation is to be sought in the high content of garnet, in which the andradite component absorbs a high percentage of the normative An-molecules.

In many cases the plagioclase is almost universally developed as antiperthite, with coarse lamellae or irregular blebs of orthoclase (Fig. 5). The plagioclase is then often without twinning, but non-perthitic plagioclase can also be free of twinning, or the twinning lamellae are so finely developed that they escape attention. Of late both the general occurrence of antiperthite and the absence of twinning in the plagioclase have repeatedly been emphasized as characteristic of rocks of the charnockite series.

The pyroxenes of the basic charnockites are diopside and hypersthene. Diopside is in general more abundant than the orthorhombic pyroxene. The two pyroxenes are often found in intergrowth, diopside then generally forming the kernel, surrounded by a more or less regular reaction rim of granular hypersthene (Fig. 6).

Optical determinations of diopside from a basic charnockite from Träslövsläge give the following properties:

Plane of optical axes // (010). $2\ V_\gamma = 59°$. c/Z 42°.
$n_\alpha = 1.692$, $n_\beta = 1.698$. $n_\gamma = 1.718 \cdot n_\gamma = n_\alpha = 0.026$.

According to Winchell's tables (1947) this would correspond to a composition of 50 % diopside, 42% hedenbergite, and 8% clinoenstatite-clinohypersthene.

Larger individuals of diopside are often full of orientated lamellae of ilmenite or haematite-ilmenite.

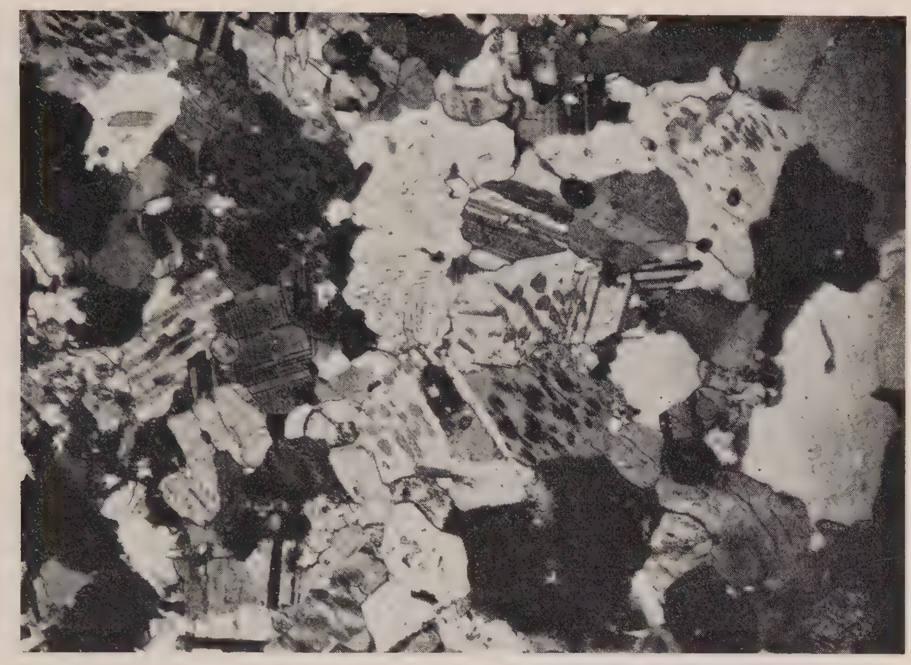

Fig. 5. Typical texture of a basic charnockite, rich in antiperthite. ×40. Railway bifurcation by Lassabacka.

The hypersthene of the basic charnockites from the same locality is in general strongly pleochroic with X purple-violet,[1] Y pale reddish-yellow, Z pale green. The plane of the optical axes is // (010). $2\,V_\alpha$ 58—60°,

$$n_\alpha = 1.699,\ n_\beta = 1.708,\ n_\gamma = 1.714,\ n_\gamma - n_\alpha = 0.015.$$

According to R. WALL's tables in his "Critical review of the data for a revision of the enstatite-hypersthene series", the composition would be 52 % enstatite and 48 % hypersthene.[2]

Not infrequently an apparent oblique extinction of up to 12° is to be observed. The same has been recorded by RAMA RAO from the charnockites in Mysore and by Washington from Holland's original localities in Madras. An explanation has been given previously (p. 239; cf. Rama Rao 1945, p. 22).

Garnet is universally present in the form of rounded grains, attaining up to 20 volumetric % of the mineral association. The colour is throughout pale purple-violet.

ADAMS[3] has described a basic charnockite (garnetiferous orthoclase norite) from Ceylon with 21.51 modal percentage of pale pink garnet. The analysis of this rock — as presenting a type likewise exceptionally rich in garnets — is given for comparison in Table I, though in other respects the chemical composition is different.

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[1] according to Radde's "Internationale Farben-Skala". (cf. p. 238.)

[2] Min. Mag. Vol. 24 (1935) p. 165. WINCHELL's tables give an essentially lower percentage of hypersthene molecule. (Winchell, Elements of Optical Mineralogy, 1948, p. 218.)

[3] ADAMS, p. 482.

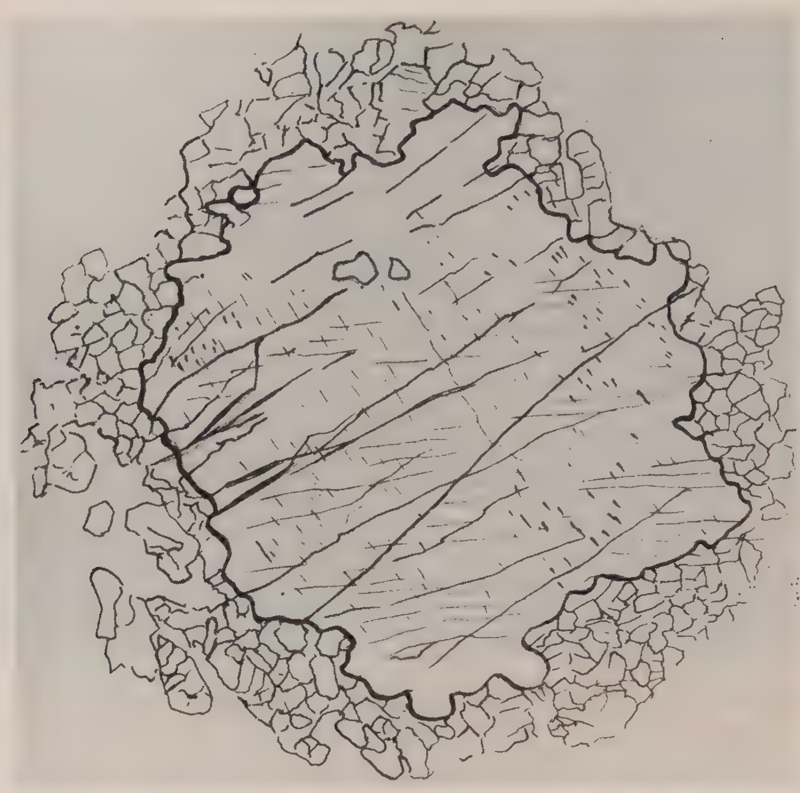

Fig. 6. Diopside fringed with small granular grains of hypersthene. × 65. Träslövsläge.

The few stray grains of hornblende are of a greenish-brown colour. X pale yellow, Y brownish-green, Z olive green.

Biotite is nearly always present, but generally only in solitary flakes.

All the rocks belonging to this basic type are rich in ore minerals. According to Ramdohr's investigation, ilmenite and haematite-ilmenite are most usual.

In one respect specimens from Lassabacka deviate from this general mineral composition. The hypersthene of these rocks shows only a faint pleochroism in contrast to the strong pleochroism of most of the other basic charnockites.

A second group of rocks belonging to the basic charnockites only deviates from the former group in having a larger content of hornblende, although this mineral does not attain a dominant place among the constituent mafic minerals. Typical rocks of this category are found round about Träslövsläge, at Getakulla and at Varö. All have the same xenomorphic granular textures as those in the former group, with the same general mineral composition. The brownish-green hornblende is the same as that sporadically found in the above-mentioned type. The hypersthene is also of the same highly pleochroic type.

Apart from the more dominant content of hornblende, the declining content of antiperthite presents a noticeable difference. In many sections it is altogether absent, as for example in many specimens from around Träslövsläge.

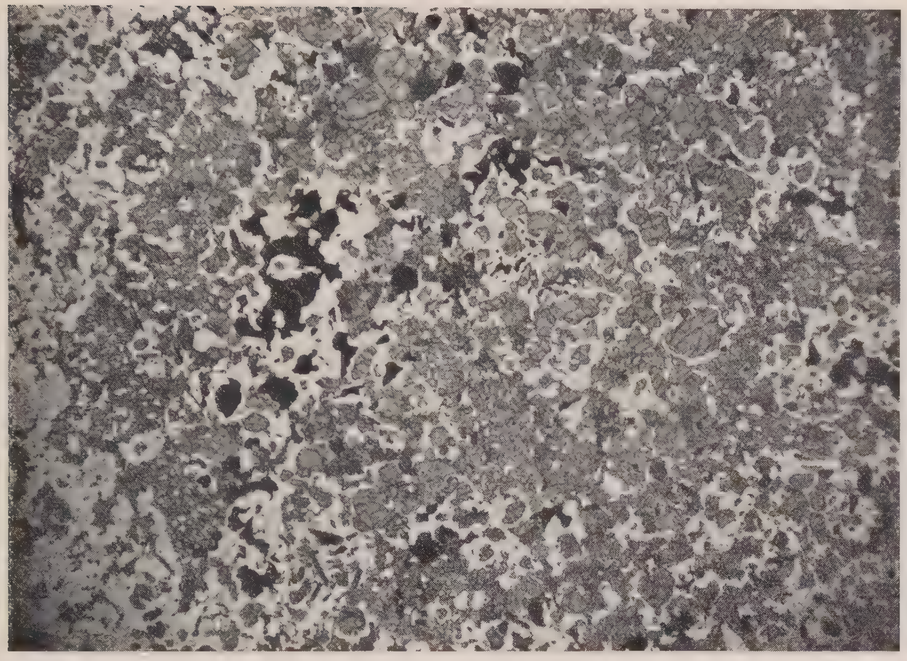

Fig. 7. Texture of basic charnockite. Diopside (poikilitic), hypersthene, garnet and ore. × 9. Klastorp.

All types are very rich in garnet of the same character as in the former type. Biotite is also present in a somewhat variable content, though mostly in the form of small dispersed flakes. Ore minerals are still frequently observed in the form of ilmenite, haematite-ilmenite and magnetite.

A third group of the basic charnockites deviates in several respects from the foregoing two types. It is characterised by a still higher content of hornblende, which has now become a predominating component in relation to the pyroxenes. Hypersthene is subordinate in these rocks but retains its high pleochroism (// X purple-violet). Diopside has a more marked light-green colour. Antiperthite is to be seen only sporadically; on the other hand the plagioclase shows better developed twinning. Orthoclase now appears more frequently in the form of self-contained individuals. The hornblende tends to become browner in colour with pleochroism X sallow yellow, Y yellowish-brown, Z greenish-brown. All these rocks are still very rich in garnet, often in larger individuals than usual in the types previously described. This third type is found in many small and isolated occurrences within the whole western part of the charnockite field.

On the whole, however, the basic charnockites now described maintain a uniform character in respect of their general mineral composition. The dissimilarities are mostly restricted to the content of hornblende in relation to the pyroxenes. One can, however, find types deviating in different respects more locally represented.

For example, the dark rocks from the quarry at Voen in Träslövsläge, though in outward appearance identical in every respect with the normal basic charnockites in

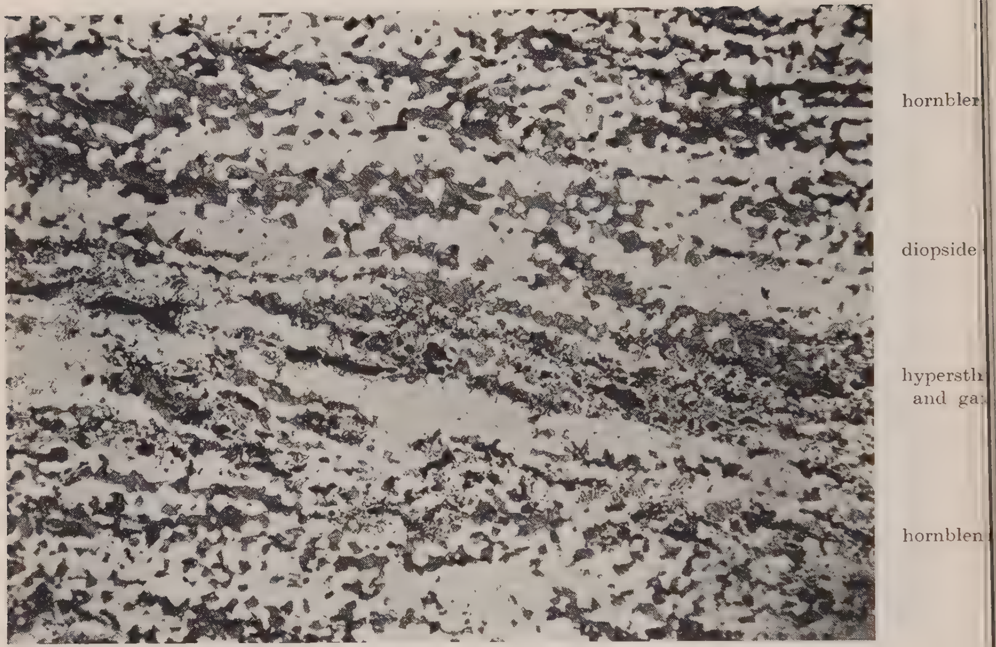

Fig. 8. Granulose structure in basic charnockite. Central zone with hypersthene, garnet and ore, flanked by zones with diopside and with hornblende. ×9. Gödestad.

the immediate vicinity, differ in being almost devoid of hypersthene and garnet. The usual antiperthitic development of the felspars is also absent. Field relations, however, combine this type with the adjacent normal basic charnockites.

Specimens from the islands of Sadeln and Balgö, near the NW border of the charnockitic area, exhibit similar deviations. Garnet is again absent. Only a few grains of faintly pleochroic hypersthene are to be seen, whereas diopside is abundant. The hornblende is of a lighter colour than usual in these rocks, with X practically colourless, Y and Z light brownish-yellow.

The basic charnockites from south of Klastorp show deviations of another character. Some specimens are still representative of the normal development of the basic charnockites with an intermediate content of hornblende, as described above. Larger crystals of diopside are often riddled with felspar chadacrysts (Fig. 7). Other specimens from the same locality, though similar in outward appearance, exhibit under the microscope a different aspect. The rocks are devoid of garnet, and in many cases now also of biotite, whereas hornblende of a more greenish tinge is plentiful. The most striking dissimilarity, however, concerns the pyroxenes. Both hypersthene and diopside, here occurring in about equal amounts, are for the most part developed in the form of small drop-like blebs, uniformly scattered over large parts of a section. The same is the case with the basic charnockites from Gödestad. In the femic streaks of the granulose rock hypersthene, diopside and — in this case — also garnet occur in drop-like aggregations in alternating stripes (Fig. 8).

The basic charnockites from both Klastorp and Gödestad are without antiperthitic felspar. They are both exceptionally rich in apatite in large grains.

To summarise the characteristic features of the basic charnockites of the Varberg district, we may say that they all retain the same outward appearance of fine-grained rocks, dark green to black in colour. As regards their mineral composition, they differ principally in respect of the content of hornblende and the relative proportions of the two pyroxenes. The type rocks are practically free from hornblende and biotite, the principal constituent minerals being antiperthite, diopside, a highly pleochroic hypersthene and a very high content of garnet. The plagioclase is often untwinned, or the twinning is so fine that it can only be observed in favourable positions with high microscopic power.

Subdivisions are characterised by a successively higher content of hornblende. The antiperthitic development of the felspars then generally decreases or is absent, as is also the content of garnet. The proportions between diopside and hypersthene are very variable. In most cases diopside predominates.

All the basic charnockites in question are rich in ore minerals, principally ilmenite, haematite-ilmenite and magnetite.

Two analyses have been made of rocks belonging to this division (Table 1). No. 1, from Lassabacka, is a type specimen, free of hornblende, except for a few small stray flakes. Its mineral composition is made up of antiperthite, acid andesine, diopside, hypersthene and garnet as essential minerals with a high content of ore minerals. Orthoclase is almost exclusively restricted to the antiperthite. No 2, from Träslövs-

Table I.

Analyses of basic charnockites.

	1	2	3	4	5
SiO_2	44.60	45.00	50.04	47.00	51.24
TiO_2	5.12	2.40	1.93	0.69	0.95
Al_2O_3	14.36	16.62	11.65	15.59	19.74
Fe_2O_3	5.73	6.05	2.63	1.29	5.10
FeO	11.64	8.97	15.76	10.28	6.38
MnO	0.20	0.31	—	0.15	0.14
MgO	5.89	7.24	5.58	8.88	2.64
CaO	8.72	9.50	7.89	13.75	7.52
BaO	—	—	—	0.01	—
Na_2O	2.15	2.76	3.08	1.70	3.40
K_2O	1.37	0.96	0.89	0.07	2.65
P_2O_5	0.00	0.00	0.20	0.07	0.68
S	—	—	—	trace	0.13
H_2O^{-105}	0.00	0.06	—	0.14	—
H_2O^{+105}	0.14	0.16	0.19	0.40	—
	99.92	100.03	99.84	100.02	100.57
Sp. gr.	3.16	3.19	3.02	3.16	

1. Basic charnockite, Lassabacka, Varberg.
2. Basic charnockite, Högahalla, Träslövsläge.
3. Basic charnockite, (hornblende norite), St. Thomas Mt. Madras. (H. S. Washington, Am. Journ. of Sc. Vol. 41, 1916, p. 330).
4. Basic charnockite (basic garnetiferous norite) Niapa Hill, Uganda. (A. W. Groves, Quart. Journ. Vol. 91, 1935, p. 170).
5. Basic charnockite (garnetiferous orthoclase-norite) on the road Colombo-Ratapura. (F. D. Adams, Canadian Journ. of Research, 1929, I, p. 482.

Table I (cont.).

	1	2	3	4	5
Niggli Values:					
si	102.0	97.1	118.2	96.9	135.3
qz	−25.2	−31.3	−15.4	−17.1	−17.1
al	19.3	21.1	16.2	18.9	30.7
fm	52.6	49.8	55.4	47.2	34.9
c	21.3	22.0	20.0	30.4	21.3
alk	6.8	7.1	8.4	3.5	13.1
k	0.29	0.19	0.16	0.02	0.34
c/fm	0.41	0.44	0.36	0.64	0.61
Norms:					
Q	—	—	—	—	0.60
or	8.08	5.59	5.00	0.56	16.12
ab	18.19	22.25	26.20	14.15	28.82
an	25.50	30.07	15.29	34.75	30.30
ne	—	0.70	—	—	—
di	14.43	13.67	19.43	25.04	2.29
hy	13.83	—	20.27	5.22	11.54
ol	1.71	14.20	5.63	15.68	—
il	9.73	4.56	3.65	1.37	1.67
mt	8.31	8.77	3.71	1.86	7.52
ap	—	—	0.34	0.34	1.68
pr	—	—	—	—	0.25
sal	51.77	58.61	46.49	49.46	75.84
fem	48.01	41.20	53.03	49.51	24.85

1. III : 5 : 4 (3) : 4	Auvergnose	or : ab : an	15.61 : 35.13 : 49.26
2. III : 5 : 4 : 4	Auvergnose	or : ab : an	9.65 : 38.42 : 51.93
3. III : 5 : 3 : 4	Camptonose	or : ab : an	10.75 : 56.36 : 32.89
4. III : 5 : 4 : 5	(persodic)	or : ab : an	1.13 : 28.61 : 70.26
5. II : 5 : 3 : 3	Shoshonose	or : ab : an	23.43 : 38.30 : 40.27

läge, differs only in that hornblende occurs to a small extent. As seen from the analyses, the two rocks are very similar in chemical composition though taken from localities far apart.

For comparison, three analyses of some typical basic charnockites are given. No. 3 is from St. Thomas Mt., Madras, Holland's original locality. No. 4 is from Niapea Hills, Uganda, chosen as representing a very closely related basic charnockite from another continent.

Analysis No. 5 of the rock from Ceylon diverges in composition, inasmuch as it has a considerably higher content of potassium, the normative 'or' being double any of the other analyses. Adams named the rock 'garnetiferous orthoclase norite'. I have included the analysis because of the high content of garnet (modal 21.51 %), in which respect the rock is similar to the Varberg basic types from Lassabacka and Träslövsläge.

As can be seen, the basic rocks from Varberg are almost identical in chemical composition with the Indian and African basic charnockites. They all fall within the same class and order of the quantitative system and differ only insignificantly in respect of position in rang and subrang. The Niggli values are practically identical.

The basic charnockites of the Varberg district would, in a normal petrographical classification, represent norites, hyperites or dolerites, according to their petrological position. A discussion on the relations between the basic charnockites and igneous rocks of normal petrological origin will be deferred to a later section (p. 283), these questions being closely connected with the origin and metamorphic evolution of the whole complex of charnockite rocks.

2. The intermediate charnockites

(The former intermediate division of the charnockite series)

As already indicated, the intermediate charnockites exhibit a much more variable composition than is found in the basic types. Even from the same quarry specimens may be of varied appearance and in chemical analyses of rocks taken in adjacent localities the silica content varies from 53.96 to 61.86 % SiO_2.

We may take the large Fästningsberget quarry (Fig. 9), close to the ancient fort of Varberg, as representative of the intermediate charnockites and at the same time as showing many of the characteristic variations of this division.

On the whole the minerals are much the same as in the rocks of the basic division, though occurring in different proportions.

Orthoclase is now frequently occurring in independent individuals instead of being principally limited to antiperthitic intergrowth. Antiperthite is generally present but may be abundant in one specimen, rare in another. The plagioclase, both in individual crystals and in antiperthitic intergrowths, is oligoclase generally with a composition of about Ab 75, An 25.

Diopside is generally the predominant pyroxene, often developed in large individuals. Its optical constants are on the whole the same as in the basic charnockites. A difference, on the other hand, is found in the development of the pyroxenes. In the basic rocks the hypersthene was usually found in the form of small strongly pleochroic grains, surrounding larger diopside particles. In the intermediate rocks from the Varberg quarry, the hypersthene shows but faint pleochroism. In some sections it is practically non-pleochroic. It is also now developed in much larger individuals, often in intergrowth with diopside.

Optical determinations of hypersthene of rocks from two typical intermediate charnockites yield the following data:

1. $2V_\alpha$ over 71° n_α 1.728 n_γ 1.745 $n_\gamma - n_\alpha$ 0.17
2. $2V_\alpha$ over 65° n_α 1.742 n_γ 1.761 $n_\gamma - n_\alpha$ 0.19

According to R. Wall's table[1], the determinations of

No. 1 indicates a composition of 68 % hypersthene and 32 % enstatite
No. 2 » » » » 75 % » » 25 % »

Wall's table again gives higher percentages for hypersthene than do those of Winchell[2].

In one respect the optical determinations are unexpected. A higher content of the Fe-dominant hypersthene component has generally been associated with stronger pleochroism. In comparison with the composition of the hypersthene in the basic charnockites, the reverse is here indicated. (48 % hypersthene molecule with strong

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[1] Min. Mag. 24 (1935) p. 165.

[2] Elements of Optical Mineralogy, 1948, p. 218 (cf. p. 241)

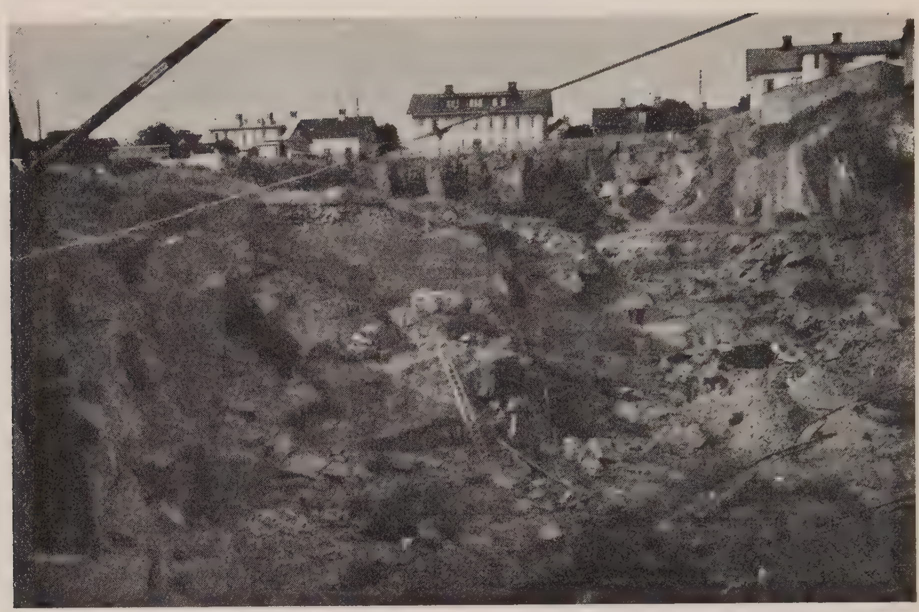

Fig. 9. The large quarry of Fästningsberget, close by the ancient fort of Varberg. The quarried rock is an intermediate charnockite.

pleochroism in the basic charnockite from Träslövsläge, as against 68 and 75 % in the intermediate charnockite from Fästningsberget with weak pleochroism). That a high iron content in hypersthenes is not always associated with strong pleochroism is evident in the case of the so-called iron-hypersthene ('Eisenhypersthene') from the eulysite from Tunaberg in Sörmland, south of Stockholm. In his description[1] of this hypersthene SUNDIUS says that in sections of normal thickness pleochroism is hardly observable. In thicker sections the pleochroism is given by PALMGREN[2] X greenish yellow, Y yellowish green, Z pale green. According to Wall's table, the optical constants $n = 1.7678$, $2V = 81°$ would give c. 83 % $FeSiO_3$ for this almost non-pleochroic hypersthene. It is therefore obvious that the iron content, i. e., the percentage of the $FeSiO_3$ component in hypersthene is not the only feature regulating the strength of pleochroism in the mineral.[3]

Dr. S. LANDERGREN has kindly determined spectrographically the minor constituents of the pyroxenes in specimens from the quarry at Fästningsberget. The result was found to be: Ti c. 1 %, Va 0.01 %, Cr 0.001 %, Mn c. 0.5 %, Co 0.01 %, Ni 0.001 %. Only Ti and Mn are found in appreciable quantities. The analysis of the non-pleochroic iron-hypersthene from Tunaberg has only 0.03 % TiO_2 and 42.23 % FeO against 0.34 % Fe_2O_3. It seems evident, then, that the strong pleochroism of the hypersthene in the basic charnockites is influenced by high contents of Ti and the Fe_2O_3 part of the total iron percentage, whereas, when the hypersthenes of the intermediate charnockites only show a faint pleochroism or are practically non-pleochroic, this is due to deficiency of Ti and Fe^{+3} in the orthorhombic pyroxene.

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[1] Sveriges Geol. Undersökning, Ser. C, No. 374, 1932.
[2] Bull. Geol. Inst. Upsala, Vol. 14, 1917, p. 133.
[3] See Winchell, Elements of Opt. Mineralogy, II, 1947, p. 220.

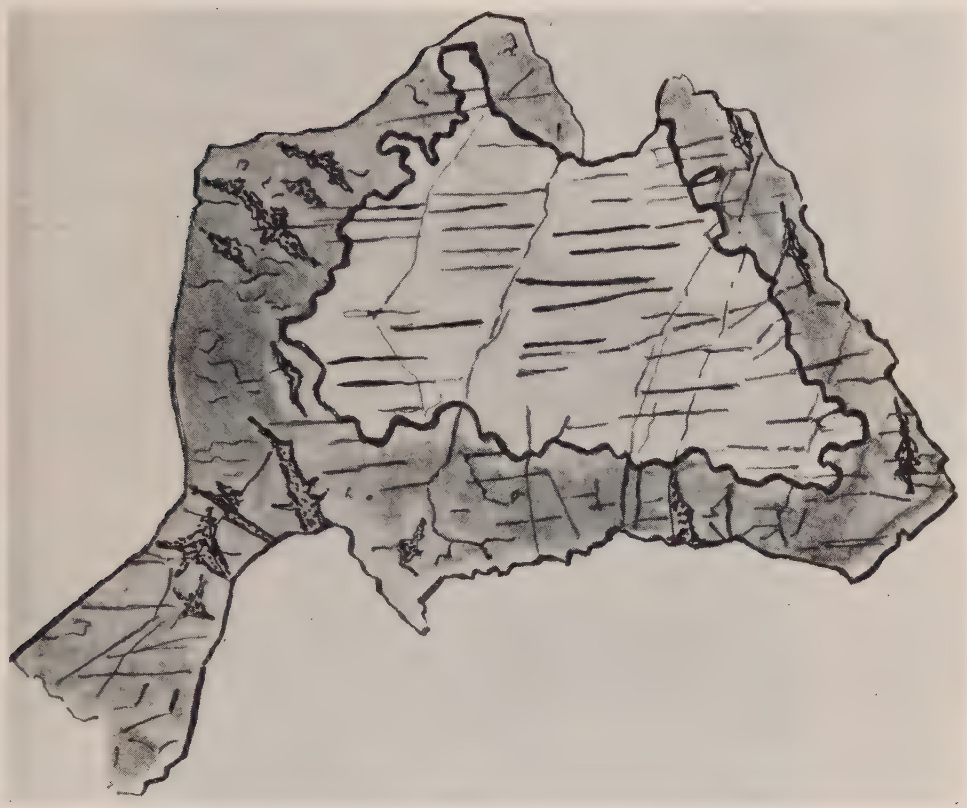

Fig. 10. Diopside encircled by hypersthene. × 130. Intermediate charnockite. Fästningsberget, Varberg.

In the rocks from the Fästningsberget quarry hypersthene and diopside are found intergrown in different ways, in one case hypersthene enveloping a diopside kernel (Fig. 10), in another the kernel itself enveloped by diopside. The two pyroxenes are also often found in homoaxial intergrowth. In these rocks the hypersthene is commonly changed into a mineral of the serpentine group, whereas the diopside is in general unaltered (Fig. 11).

Hornblende is generally abundant, predominating over the pyroxenes. It has a more greenish tinge than in most of the basic rocks of the series. The pleochroism is strong, X turbid yellow, Y olive green, Z very dark green to nearly opaque.

The garnets also deviate in appearance from those of the basic charnockites. They are of a much paler pink colour and often occur in small grains with skeleton-like encroachments.

From an intermediate type of charnockite of normal composition from Fästningsberget in Varberg, Mrs Mikkola of Helsinki has separated the garnet with a purification of 99.995 %. An analysis by Dr. Sahlbom is given under 1 in Table II. Under 2 in the same table is given an analysis of garnet from the Uganda series, representing, as far as I know, the only other analyses of garnet from typical charnockite rocks to

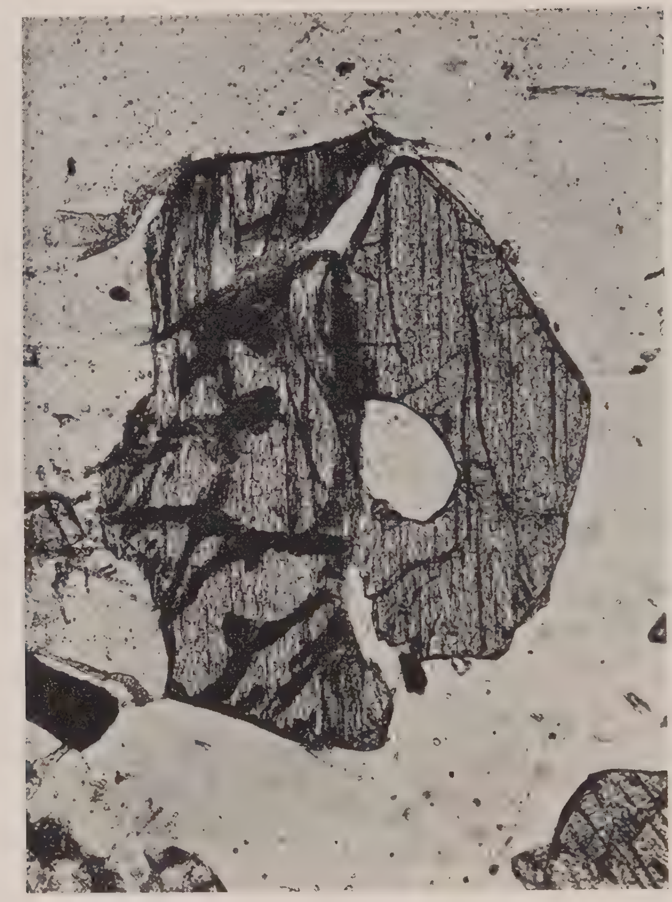

Fig. 11. Hypersthene and diopside in parallel intergrowth. × 150. Intermediate charnockite. Fästningsberget, Varberg.

have been published (Groves, p. 160.)[1]. As is to be seen, the garnet from the rock at Varberg is richer in almandine and poorer in pyrope than the garnet from an acid charnockite in Uganda.

The intermediate charnockites are singularly rich in apatite and zircon, both often in unusually large grains. Ore minerals are also abundant.

In specimens which show a marked granulose striation, the banding is due to enrichment of the mafic minerals in streaks, alternating with leucocratic bands, almost devoid of dark constituents. Antiperthite is scanty in these felspatic bands.

In many specimens from the Fästningsberget quarry one finds indications of hypogene decomposition. As already noted hypersthene is often much altered to serpentine.

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[1] I have not included an analysis by C. F. Kolderup (Bergens Museums Aarbok, 1913, No. 12, p. 32) of garnet from the labradorite series of the Bergen district, though these rocks have been regarded as petrologically associated with the charnockite series. I have, however, not been able to refer them to this group in the more restricted sense employed in this paper. (cf. p. 310).

Table II.

	1	1 a	2	2 a
SiO_2	36.70	0.612	39.55	0.659
TiO_2	0.00	—	0.21	0.003
Al_2O_3	16.58	0.1625	17.67	0.174
Fe_2O_3	12.72	0.0797	7.39	0.046
FeO	20.70	0.2880	17.93	0.249
MnO	3.00	0.0423	0.46	0.007
MgO	2.73	0.0677	14.66	0.367
CaO	7.00	0.1250	2.07	0.038
Na_2O	0.03		—	
K_2O	0.11		—	
P_2O_5	0.00		—	
$H_2O^{-105°}$	0.00		—	
$H_2O^{+105°}$	0.68		—	
	100.25		99.94	
Sp. gr.	1.808			

1. Analysis of garnet from an intermediate charnockite, Fästningsberget, Varberg. Naima Sahlbom anal.

1 a. Mol. prop. of analysis 1.

2. Analysis of garnet from acid charnockite, Uganda. A. W. Groves anal.

2 a. Mol. prop. of analysis 2 (Groves 1935, p. 160). Recalculated to 100, free from normative excess of quartz.

Composition of standard molecules

	1.	2.
Almadine ($Fe_3Al_2Si_3O_{12}$)	61.2	41.2
Andradite ($Ca_3Fe_2Si_3O_{12}$)	21.4	21.7
Pyrope ($Mg_3Al_2Si_3O_{12}$)	9.2	35.8
Spessartite ($Mn_3Al_2Si_3O_{12}$)	7.0	1.3
rest SiO_2	0.7	
rest Al_2O_3	0.4	
	99.9	100.00

Calcite is frequently present as small interstertial grains or as interpenetrations along cleavage planes, particularly in the felspars. Secondary quartz is not infrequent in lenticules of granulated grains. A few grains of epidote have been observed, and in one instance also sphene, which otherwise is completely absent in all the charnockitic rocks of the Varberg district, as is also observed in the case of nearly all other occurrences of rocks belonging to the charnockitic series. In several sections small grains of a brown pleochroic mineral occur, exhibiting the optical properties of allanite.

The presence of these minerals may indicate that rocks from this locality have to a certain degree succumbed to later alterations of a less deep-seated character than in the case of the transformation of the charnockitic rocks in general.

As further noteworthy occurrences of this type of the intermediate charnockites may be mentioned the quarries at Träslövsläge, Trönningenäs, Träslöv church, Öströö, and on the islands of Getterö and Sadeln. The rocks in all these localities have much the same appearance in respect of structure and textural development and mineral composition, as indicated above.

Antiperthite is generally present, in some cases (Öströö and Trönningenäs) abundant, but then often together with normal orthoclase-perthite. In sections from Trönningenäs one may observe antiperthite grading over to orthoclase-perthite in one and the same individual, in every detail conforming with LEGOUX's sketch of a similar transition in rocks from the charnockites of the Massiv de Man on the Ivory Coast. (Legoux, p. 35 Fig. 8).

The rocks from around Träslöv church show a tendency to develop large porphyroblastic phenocrysts of plagioclase, occasionally in parts developed as antiperthite.

In most of these localities hornblende predominates over the pyroxenes, of which diopside is more common than hypersthene. In some cases hypersthene is wholly absent. When present it is generally only faintly pleochroic and often much altered to serpentine. Garnet is present in very variable amounts. It generally exhibits extremely irregular contours as the result of deep encroachment. Rocks from Getterö and the island of Sadeln are devoid of garnet. Many specimens from Träslövsläge contain only occasional grains of pyroxene and garnet. If hornblende, too, is scarce, the composition indicates an approach to the adjacent felsic charnockites of the same localities.

Two analyses of typical intermediate charnockites are given in Table III (Nos. 1 and 2). Both are Törnebohm's original analyses and are taken from his short paper on the Varberg charnockites, then called 'Varberg granite' (l. c., p. 229).

In the eastern outskirts of Varberg town the charnockitic rocks of the intermediate division assume a somewhat different character. They are of a bluer shade than the predominating greenish-gray to greenish-brown of the intermediate group in general. They also have a more acid composition than have the previously described rocks of this division and verge towards the group of acid charnockites in the usual classification. I have therefore referred them to a sub-acid division within the intermediate charnockite group. The chemical analysis of this type from Traneberg, just east of Varberg, given in Table III, No. 5, justifies this placing. (Niggli value qz + 34.5).

Under the microscope several dissimilarities can be observed in respect of mineral composition as compared with that of the normal intermediate rocks.

Quartz is present in very varying amounts. In one section it may be scarce, in another relatively abundant. It is also more evenly distributed than in the other rocks of this division, where it generally occurs only as sub-parallel lenticules.

One would expect the blue colouring of these rocks to be caused by a blue coloration of the quartz, as has been proved from the charnockites of India. However, no distinct colouring of the quartz can be observed in this case.

Garnet and biotite are completely absent, and hornblende is either lacking or of very insignificant occurrence.

The more interesting feature of the rock in respect of its mineral composition concerns the felspars and the pyroxenes.

Plagioclase (Ab 72, An 28) predominates over orthoclase. It occurs in large, generally twinned individuals. Most of them are, however, antiperthitic, in many cases showing a singularly delicate texture. Instead of the more patchy inlay of the orthoclase lamellae in the rocks of the basic and normal intermediate group, these now attain a regularity in their orientation in well defined directions, resulting in an interlacement of striking appearance (See Pl. I, Fig. 1 and 2).

Another significant feature of this type of rock is the almost constant regular intergrowth between diopside and hypersthene, the latter now always occupying the kernel, encircled by a uniform diopside individual (Fig. 12). In these rocks the hyper-

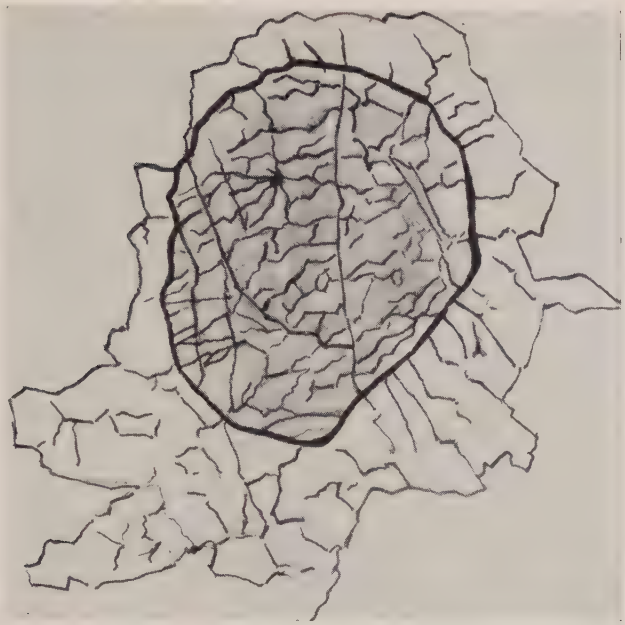

Fig. 12. Hypersthene (dark shade) surrounded by diopside. × 120. Traneberg, Varberg.

sthene is almost non-pleochroic, X and Y colourless, Z only showing a very faint light pink tinge.

This description deals with the rocks from one locality in the vicinity of Traneberg. Specimens from some other occurrences in the same neighbourhood show but slight deviations. Biotite may enter in an insignificant amount. If biotite is present, the amount of hypersthene invariably decreases or is wholly absent. When present, it then generally tends to occur in small grains, whereas diopside occurs in large individuals, poikilitically intergrown with abundant felspar chadacrysts. (Fig. 13).

The hornblende, scarce in all rocks of this sub-acid group, is of a distinctly more bluish colour than in the other intermediate charnockites. It is only faintly pleochroic, with X pale yellow, Y light green, Z light blue.

In several places one finds intermediate charnockites grading into coarse-grained leucocratic rocks, devoid or almost devoid of mafic minerals. The outward appearance is that of a purely felspathic rock of anothositic type. Quartz is often, but not always, present in small quantities.

In its most typical development, this type is found in the old quarry of Bankahalla, at Träslövsläge, and by the old mill at Trönningenäs. In Träslövsläge it was also temporarily exposed during blasting for a harbour extension.

In the rocks from the harbour, microcline and plagioclase form the only essential constituents. Perhaps the most interesting feature of the rock is that the potassic felspar and plagioclase are represented in about the same proportions. In general, felspar rocks of this nature contain either potassic felspar or plagioclase of varying composition as principal constituents. The names given in petrographical literature conform therewith (orthoclasite, oligoclasite andesinite, labradorite etc.). In inter-

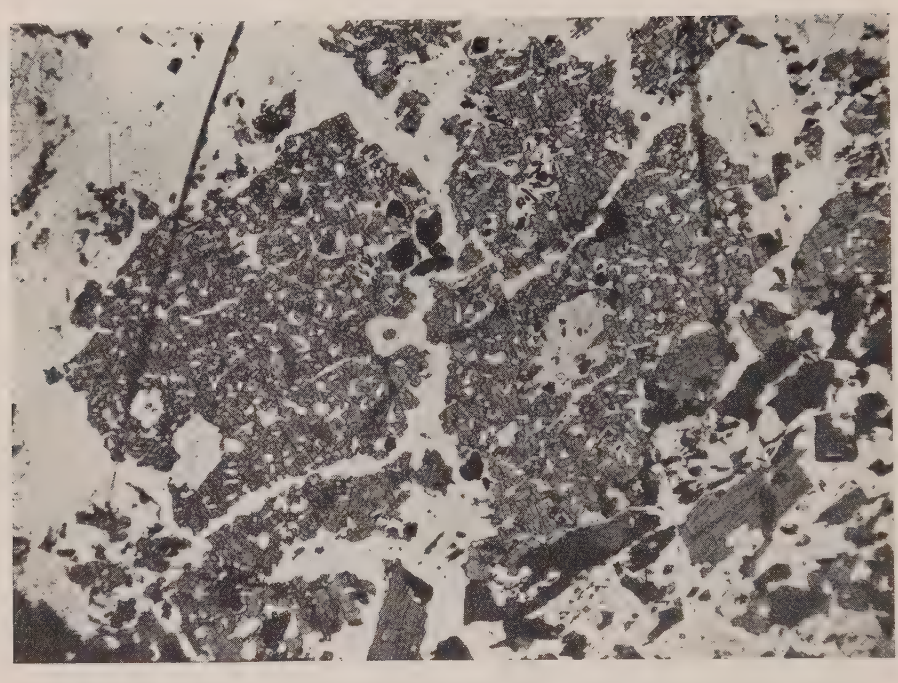

Fig. 13. Large diopside crystals, poikilitically interspersed with felspar. × 9. Sub-acid charnockite. Ekregården, NE of Varberg.

national literature one finds very few examples of rocks containing both a potassic felspar and plagioclase in about the same proportions. One such rock may be the so called vallevarite from the Ruoutevare complex in northern Sweden, described by AXEL GAVELIN.[1] No analysis is given, but from Gavelin's description, which states that the rock bears the same relation to monzonite as anorthosite to gabbro, one may conclude that potassic felspar and plagioclase occur in about equal proportions.

In the rocks from the harbour at Träslövsläge microcline-perthite in large individuals, up to 2 cm, is common. Antiperthitic development of the plagioclase is here, in contrast to the similar occurrence from Trönningenäs, absent. Stray grains of a highly decomposed pyroxene can be seen in the interspaces between the larger felspar individuals. The decomposition is so complete that no determination of the species has been possible. Zircon is in this rock exceptionally abundant in unusually large individuals.

In similar rocks from the neighbouring quarry of Bankahalla there is no trace of any mafic minerals except for grains of ore.

Specimens from Trönningenäs are in most details of the same character as described from Träslövsläge. In one case, however, an essential difference is to be observed. The potassic felspar is now orthoclase instead of microcline. The large crystals show well-defined Carlsbad- and occasionally also Baveno twins. In some cases large plagioclase crystals are antiperthitic with orthoclase in small-grained blebs (Fig. 14). Here and there myrmekite is developed around the orthoclase individuals (Fig. 15). Some freely developed quartz is also often present along with small aggregations of

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[1] Geol. För. Förh., Vol. 37, 1915, p. 19.

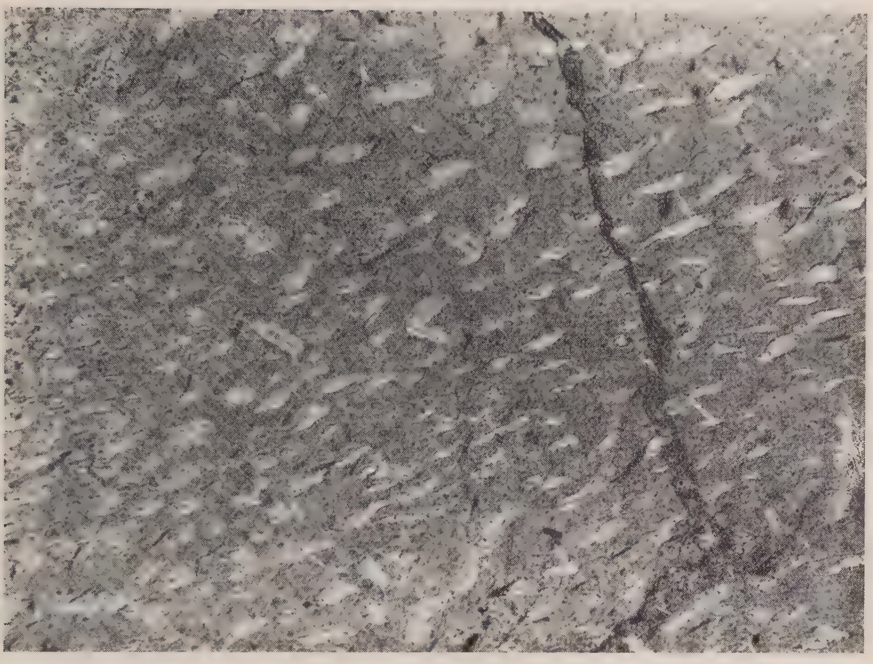

Fig. 14. Anthiperthite in coarse-grained leucocratic charnockite. × 150. By the old mill south of Trönningenäs.

hornblende, garnet, diopside and apatite. Garnet is also found in well-defined zones around grains of titanomagnetite (Fig. 16). Hornblende is also found in similar zones around ore grains.

Several other occurrences of similar rocks are to be found within the charnockitic area of the Varberg district. They are, however, of only insignificant dimensions and have the character of local coarse-grained segregations of felspatic composition. Even the more extensive occurrences at Träslövsläge and Trönningenäs seem only to represent casual leucocratic segregations near the contact with the surrounding gneiss. The occurrence of microcline and microcline-perthite in the rocks from round Träslövsläge and of orthoclase and well developed antiperthite in the rocks from Trönningenäs, must indicate that the final crystallisation of these leucocratic types took place under different petrogenetical conditions. These circumstances seem to strengthen the assumption that the assemblage of these rocks does not represent a definite petrographic unit. This seems the more plausible since, in some of the laminated charnockites of the district, one may encounter leucocratic 'schlieren', wholly devoid of mafic minerals and, though more fine-grained, of the same general composition as some of the felspathic rocks described above. (See Fig. 4, p. 240).

Though the consanguinity of anorthositic rocks with rocks of the charnockitic series has already been questioned by Holland and later by others, the occurrences within the Varberg area are not of such a nature that there they can be said to support such an assumption. This question is discussed in more detail under a subsequent heading (p. 309).

An analysis of the leucocratic rock from Träslövsläge is given in Table III, No. 3.

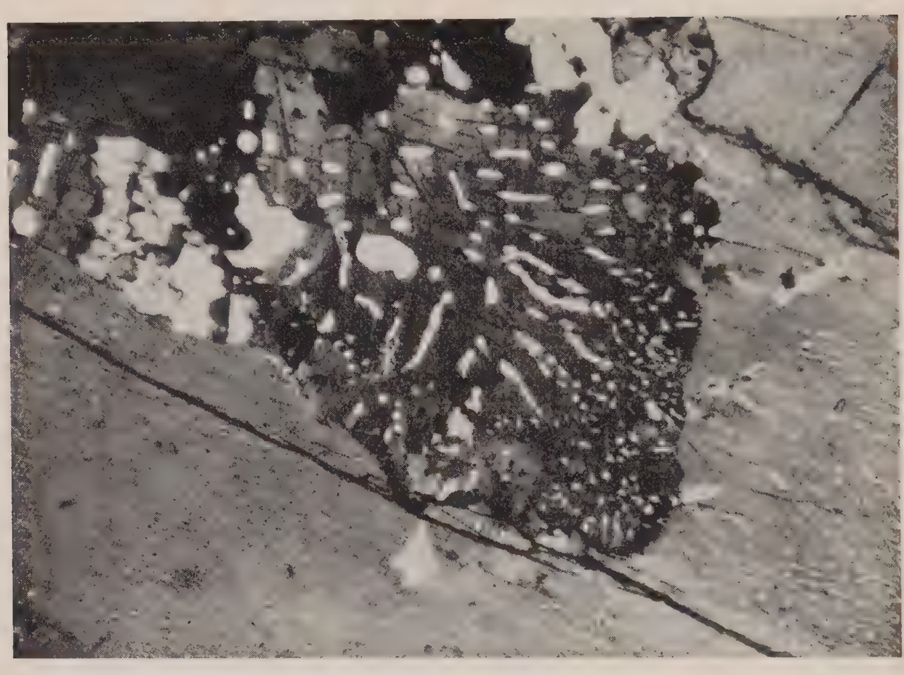

Fig. 15. Myrmekite bordering on antiperthite in coarse-grained leucocratic charnockite. × 45. By the old mill south of Trönningenäs.

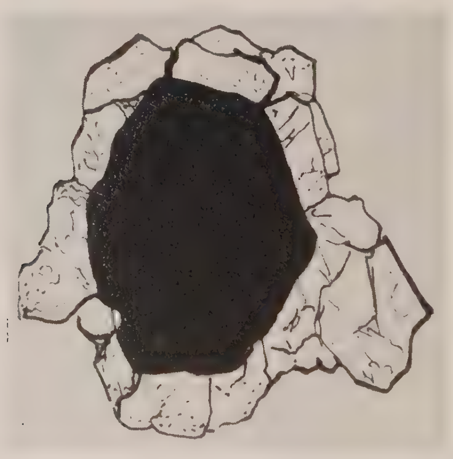

Fig. 16. Aggregate of small garnets around an ore mineral. × 200. Trönningenäs.

A totally different group of rocks, in reality only on account of their silica content grouped together with the intermediate charnockites, are found in a wide area away from the coastal line. The principal occurrences are situated on a stretch from Trönninge to the east of Himle and Tvååker.

The rocks in question are all extremely fine-grained. No minerals are discernible to the naked eye. As already noted under a previous heading (p. 237), they resemble a dark quartzite more closely than rocks of the charnockite series.

As a typical representative of this group we may take the analysed rock from the northern locality between Björka and Trönninge. The most remarkable feature of the mineral composition is that diopside is completely absent, whereas a highly pleochroic hypersthene is abundant in small grains. The dominant mafic mineral is, however, an amphibole of a somewhat unusual type. It is of a distinctly light bluish colour with a pleochroism X practically colourless, Y greenish-blue, Z bluish-green. $2V$ 73° n_α 1.650, n_β 1.657, n_γ 1.665. The extinction angle is c/Z 24°. Another unusual feature is the sporadic presence of scapolite in small particles, occurring in streaks in the rock.

Antiperthite is not developed in rocks from this locality. The plagioclase is instead zonal, the basic core Ab 40, An 60. Garnet is not present. Zircon is also completely absent, and apatite is scarcer than in the intermediate rocks in general.

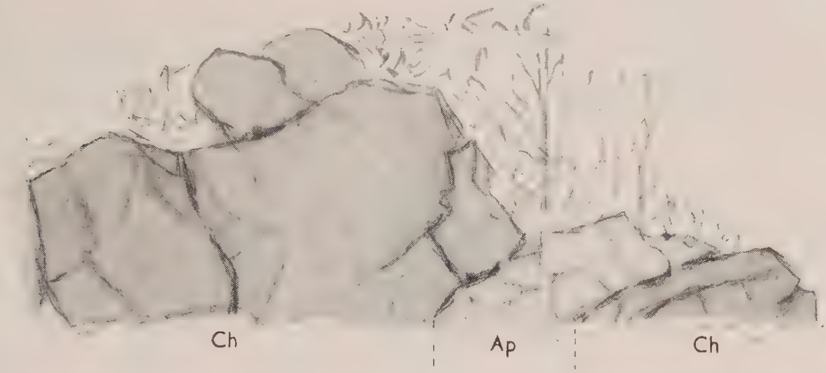

Fig. 17. Sketch of an exposure of black aphanitic charnockite (silicified basic charnockite) Scale 1 : 150. Getakulla. Ch = charnockite. Ap = aplite granite.

Megascopically identical rocks from Getakulla (Fig. 17) differ in some respects as regards their mineralogical composition. Antiperthite is again a prominent feature in the rock, with coarse laths of plagioclase. A yellowish-green hornblende predominates among the mafic minerals. Diopside and a now faintly pleochroic hypersthene vary in relative quantities. In some sections hypersthene may be absent. Both pyroxenes are for the most part much decomposed. As in most rocks of this group, garnet is completely absent. Zircon can be abundant in one section, in another present only as stray grains. Apatite and ore minerals are abundant.

Specimens from other localities exhibit much the same character as that of the rocks described, or possess features intermediate between them. Some of the rocks are microscopically laminated; the femic streaks are composed of hornblende with relatively insignificant amounts of pyroxenes. The rocks from an occurrence near Träslöv church are of interest in that they exhibit a recurrence of garnet in small quantities. The hornblende is in some sections bluish, as in the type first described, in other sections yellowish-green with X light yellow to nearly colourless, Y a turbid yellowish-green, Z greenish-yellow.

In all the types of this group biotite is present in varying amounts. Quartz is relatively abundant.

An analysis of the rock from Trönninge is given as No. 5 in Table III. Its petrological position will be treated below.

One may sum up the general character of the rocks belonging to this group as follows: all the rocks are very fine-grained or aphanitic and very dark in colour. Antiperthite is in some cases well developed. Hornblende is the predominating mafic mineral, generally yellowish-green in colour but sometimes of a distinctly more bluish shade. The two pyroxenes are present in very variable amounts. In some cases one or the other may be completely absent. Hypersthene, and sometimes also the diopside, is in general much decomposed. Calcite is often present in the form of fine fissures along the felspar cleavages. Except in one case, garnets are totally absent.

As is to be seen from the analyses in Table III and perhaps still more obviously from the Niggli values and the norms, the intermediate rocks, in contrast to the basic division, exhibit considerable variations.

The two first analyses of rocks from the quarry at Fästningsberget, within the town of Varberg, and from Apelviken, 2 km south thereof, may be said to represent the most typical development of this group. The content of quartz is evidently variable, even within this restricted area. The Niggli values of *qz* vary from – 12.0

Table III.

Analyses of intermediate charnockites and related rocks.

	1	2	3	4	5
SiO_2	53.96	60.12	61.86	62.04	51.60
TiO_2	2.45	0.95	0.80	0.60	1.00
Al_2O_3	15.98	16.63	17.56	18.49	19.96
Fe_2O_3	2.76	2.19	1.24	1.65	7.06
FeO	6.16	4.79	4.03	1.50	3.60
MnO	0.27	0.10	0.06	0.08	0.16
MgO	1.58	0.82	1.87	0.87	3.04
CaO	5.82	3.75	5.00	2.04	10.44
BaO	0.19	0.21	—	—	—
Na_2O	4.18	4.73	4.00	4.49	1.80
K_2O	3.72	4.25	3.08	7.69	0.50
P_2O_5	1.85	0.77	trace	0.00	0.50
Cl	—	—	—	—	0.10
FeS	0.35	—	—	—	—
$H_2O^{-105^\circ}$	—	—	0.20	0.04	0.00
$H_2O^{+105^\circ}$	0.27	0.25	0.70	0.52	0.58
	99.54	99.56	100.40	100.01	100.34
Sp. gr.	2.87	2.77	2.75	2.63	2.88

1. Intermediate charnockite (previously named 'Varberg granite') Apelviken, south of Varberg. (A. E. Törnebohm, S. G. U. Ser. Ba, Nr. 6, 1910, p. 20).
2. Intermediate charnockite, Fästningsberget, Varberg. Ibid.
3. Sub-acid charnockite, Traneberg, Varberg.
4. Coarse-grained leucocratic charnockite, Träslövsläge.
5. Fine-grained dark charnockite, between Björka and Trönninge (silicified basic charnockite).

Table III (cont.).

	1	2	3	4	5
Niggli Values:					
si	168.8	213.5	215.7	236.9	135.8
qz	− 12.0	9.9	34.5	− 4.3	15.0
al	29.5	34.9	36.1	41.6	31.0
fm	30.7	24.8	24.9	14.7	34.2
c	19.6	14.4	18.7	8.4	29.4
alk	20.2	25.9	20.3	35.3	5.2
k	0.37	0.37	0.34	0.53	0.15
c/fm	0.64	0.58	0.75	0.57	0.86
Norms:					
Q	3.90	7.26	11.84	1.17	14.96
or	21.68	25.02	18.20	45.41	2.95
ab	35.63	39.82	33.79	37.96	14.47
an	13.90	11.68	20.88	7.62	45.30
sc	—	—	—	—	0.16
di	2.57	1.89	3.23	2.00	2.49
hy	8.12	6.68	8.21	1.77	6.41
il	4.71	1.82	1.52	1.14	1.90
mt	3.94	3.25	1.81	2.38	9.24
ht	—	—	—	—	0.69
ap	4.37	1.68	—	—	1.18
sal.	75.11	83.78	84.71	92.16	77.84
fem.	23.71	15.32	14.77	7.29	21.91

1. II : 5 : 2 : (3) 4	Akerose	or : ab : an	30.44 : 50.04 : 19.52
2. II : 5 : 2 : 4	Akerose	or : ab : an	32.70 : 52.04 : 15.26
3. II : 4 : 3 : 4	Tonalose	or : ab : an	24.98 : 46.37 : 28.65
4. I : 5 : 2 : 3	Pulaskose	or : ab : an	49.91 : 41.72 : 8.37
5. II : 4 : 4 : 4	Bandose	or : ab : an	4.70 : 23.07 : 72.23

to + 9.9. On the other hand the felspars show good agreement. The proportions or:ab:an are generally about the same, and in both cases the plagioclase is an intermediate oligoclase.

The third analysis in Table III deals with the rocks of sub-acid composition, representing a local, somewhat more acid, sub-species of the intermediate charnockites, but at the same time representative of the most acid type of typical charnockite rocks within the Varberg area.

No. 4 in Table III is the analysis of the leucocratic felspar rock from Träslövsläge. The rock is all but free from modal quartz (Niggli value *qz* — 4.3). The norm confirms the petrographical determinations that potassic felspar and an acid plagioclase constitute over 90 % of the rock in about the same proportions.

The fifth analysis is that of the dark fine-grained to aphanitic rock of wholly deviating chemical composition. The normative content of 'an' is more than double that of any of the four other analyses of the intermediate charnockites and even much higher than in the basic charnockites of the area. The Niggli values for *c* and *alk* correspond closely to those of the basic charnockites. From Landergren's examination of the ferrides (see appendix II) we also find the high content of V and Ni in common for the rock in question and for the basic charnockites. One is tempted to explain these abnormal rock types as representing an intermediate stage towards the conversion to basic charnockites which, in connection with a minor volatile influx, manifested in the presence of scapolite, have become highly silicified. The secondary addition of silica in the form of free quartz would then explain the abnormal position of these rocks within the acidic boundary of the intermediate charnockites.

3. The felsic charnockites

What have been designated felsic charnockites within the Varberg district, in many cases probably corresponding to what have been called 'granulites' in close connection with charnockites from other regions, are rocks which in general exhibit uniform characteristic features. They all have a pronounced felsic composition. Minerals of the pyroxene group are absent, and garnet is only found in isolated grains. Hornblende is also lacking in most cases, and if present it is generally only found in small aggregations together with biotite, which is the only ferro-magnesian mineral of more general occurrence if any mafic mineral at all is met with. Quartz is always relatively abundant.

The felsic charnockites are found closely associated with the intermediate charnockites or form large independent rock units.

The outward appearance is somewhat variable. In general, rocks of this type have a greenish-gray colour in common with the intermediate charnockites. This is especially the case at Träslövsläge. In other occurrences, especially at the sizable exposures round Himle station, where they are the only type present, they often have a somewhat more reddish tinge. All exhibit the typical brownish weathering characteristic of the whole series.

Rocks belonging to this division are found well exposed in several quarries round about the village of Träslövsläge, along with the usual intermediate charnockite. Quartz is abundant in comparison with the content in the neighbouring rock. The felspars are plagioclase (an acid oligoclase) and either microcline and microcline-perthite or, more rarely, orthoclase and orthoclase-perthite.

The plagioclase is generally developed in large twinned individuals. Antiperthite has only been observed in insignificant development in a few sections.

Biotite, when present, is often much decomposed. Calcite is found in stray grains throughout many sections. As accessory minerals zircon and apatite are, as usual, abundant. Ore minerals, on the other hand, are scarcer than in the adjoining charnockite rocks.

The more isolated, but on the other hand more prominent, rocks of this group at and around Himle station have much the same general composition as those from Träslövsläge. They are perhaps still more characteristic of this facies in being almost destitute of mafic minerals. Hornblende is entirely absent, and in many cases biotite is only found in stray flakes. It is, as pointed out above, generally much decomposed. The potassic felspar is now only microcline, often partially developed as microcline-perthite.

Analyses of two typical rocks of felsic charnockites are given in Table IV. No. 2 is from an old quarry near Himle station, No. 3 from Träslövsläge.

4. The aplite granite

The aplite granite of the Varberg charnockite district is very uniform, both with regard to its general appearance in the field and its mineral composition. It is a fine-

Table IV.

Analyses of aplite granite, of felsic charnockites and of a hybrid rock.

	1	2	3	4
SiO_2	73.72	72.32	68.12	68.16
TiO_2	0.20	0.16	0.30	0.30
Al_2O_3	13.58	14.46	15.16	14.94
Fe_2O_3	0.60	1.24	1.48	0.98
FeO	1.12	0.67	1.69	2.24
MnO	0.02	0.02	0.05	0.10
MgO	0.14	0.33	0.73	1.12
CaO	1.04	1.78	2.40	2.56
Na_2O	2.43	3.39	2.85	3.02
K_2O	6.87	4.92	6.79	5.83
P_2O_5	trace	0.00	0.24	0.15
$H_2O^{105°}$	0.09	0.34	0.02	0.26
$H_2O^{+105°}$	0.18	0.50	0.25	0.44
	99.99	100.13	100.08	100.10
Sp. gr.	2.61	2.67	2.66	2.64

1. Aplite granite. Old quarry of Högahalla, Träslövsläge.
2. Felsic charnockite. Old quarry near Himle station.
3. Felsic charnockite. Högahalla, Träslövsläge.
4. Hybrid rock. Old quarry of Bankahalla, Träslövsläge.

	1	2	3	4
Niggli Values:				
si	421.6	383.7	305.6	301.4
qz	168.0	147.3	78.8	83.4
al	45.8	45.2	40.2	39.0
fm	9.3	10.6	16.5	19.3
c	6.5	10.1	11.6	12.2
alk	38.4	34.1	31.7	29.5
k	0.65	0.49	0.61	0.56
c/fm	0.70	0.95	0.72	0.63
Norms:				
Q	30.31	29.50	19.74	20.03
or	40.57	29.05	40.13	34.47
ab	20.55	28.68	24.12	25.68
an	5.15	8.84	8.51	10.01
C	0.27	0.33	—	—
di	—	—	1.51	1.61
hy	1.62	0.82	2.54	5.04
il	0.38	0.30	0.58	0.93
mt	0.88	1.76	2.15	1.39
hm	—	0.03	—	—
ap	—	—	0.57	0.34
sal.	96.85	96.40	92.50	90.19
fem.	2.88	2.91	7.35	9.91

1. I : 4 : 1 (2) : 2 (3) Omeose or : ab : an 61.22 : 31.01 : 7.77
2. I : 4 : 2 : 3 Toscanose or : ab : an 43.64 : 43.08 : 13.28
3. I : 4 : 2 : 2 (3) Toscanose or : ab : an 55.15 : 33.15 : 11.70
4. I : 4 : 2 : 3 Toscanose or : ab : an 49.2 : 36.6 : 14.2

grained quartz-felspar rock, light red in colour and almost devoid of mafic minerals. As is to be seen from the map, it is the predominating rock within the charnockitic area, everywhere surrounding the different types of the specific charnockite rocks.

The mineral composition is simple and very uniform. Quartz is abundant in large individuals as well as here and there in the form of myrmekitic intergrowth. The felspar components are microcline and plagioclase. Microcline-perthite, often grading into cryptoperthite, is of common occurrence. The plagioclase, subordinate in quantity, is an acid oligoclase. The only mafic mineral present, except for an occasional grain of garnet, is biotite, often more or less decomposed into chlorite and epidote. Zircon is plentiful, along with apatite and ore minerals forming the accessory constituents.

An analysis of a typical specimen of the aplite granite from the Högahalla quarry at Träslövsläge is given under No. 1 in Table IV.

The position of the aplite in relation to the charnockites of the district is a problem of special interest, as the same field connection has been reported from other occurrences of charnockite rocks. This question must be deferred to a later heading, where a relationship between the aplitic and the charnockitic rocks of the Varberg district and of other occurrences will be discussed (p. 307). It will suffice to mention here that HOLLAND, VREDENBURG, GHOSH and RAMA RAO describe 'younger', often aplitic, granites of much the same character as the Varberg rock from different Indian charnockite localities, and in all cases their genetical consanguinity (magmatic or metamorphic) with the charnockite series has been assumed. (Holland, p. 145, Vredenburg, p. 444, Ghosh, p. 40, Rama Rao, p. 103). The same is the case with the 'aplogranite' of the Massif de Man on the Ivory Coast, according to LEGOUX, who says: "Nous pouvons donc, bien que la roche 1622 (an analysed specimen of aplogranite) ne manifeste pas d'hypersthène à cause de son charactère hololeucocrate, la considérer comme le terme extrême de la série granitique magnésienne". (Legoux, p. 44).

5. The hybrid rocks

With regard to the origin of the charnockite rocks and their metamorphic evolution, the hybrid rocks, in which the incongruous rock elements can be discerned with the naked eye, are of special interest. Such rocks have been found in many places within the charnockitic area. The most outstanding localities are the old quarries at Träslövsläge and the eastern outskirts of Varberg town.

The two ingredients are always the aplitic granite and charnockitic rocks of the intermediate group or the felsic charnockites.

In the old quarries at Bankahalla and Fladahalla (Träslövsläge) one may say that the predominating rocks are composite in their general appearance. In one case the pink aplite granite may be the essential component, retaining larger or smaller streaks and bands of a greenish intermediate or felsic charnockite, whereas nearby the same charnockitic rocks may contain more or less assimilated remnants of the aplite granite. One also finds every transition from coarse admixtures of the two components to more homogeneous rocks, where one or the other of the constituents can only be identified by their different colouring. Or one may follow the gradual change of the original fragments to a stage when only faded remnants of them are left (Fig. 18.).

The inhomogeneity is also obvious under the microscope. Irregular bands of

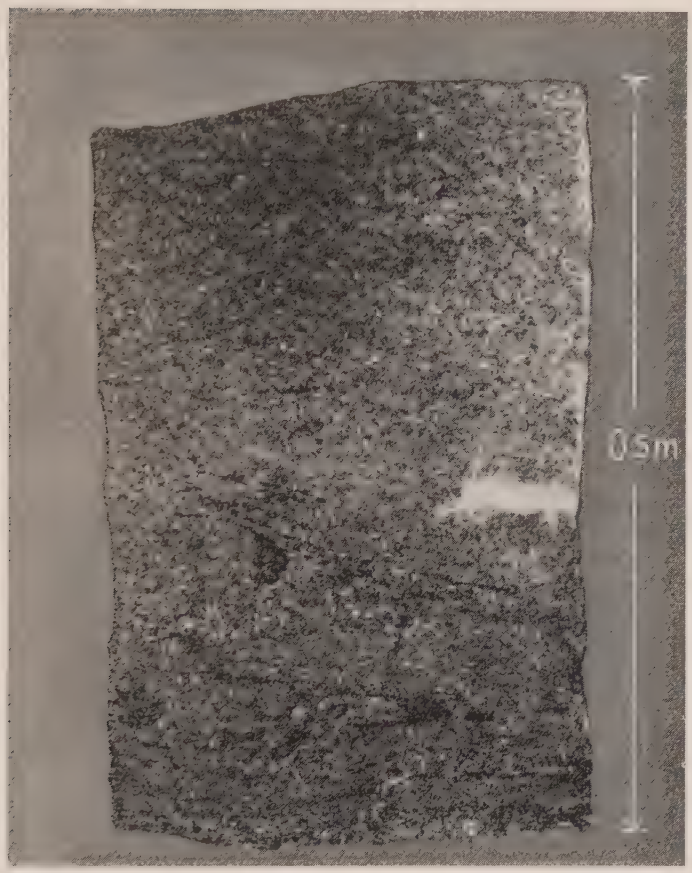

Fig. 18. Aplitic granite with faded remnants of charnockitic rock. Fladahalla, Träslövsläge.

quartz-felspar alternate with strips rich in biotite, hornblende and a much decomposed pyroxene. In the greenish charnockitic parts of the rock zircon is present in unusually large individuals. Fig. 19 shows such a large zircon crystal enveloped by apatite.

An analysis of a typical specimen of a megascopic hybrid rock is given in Table IV, No. 4. The analysis seems to afford some evidence as to the nature of the components of the hybrid rock. If we take the Niggli values of the analysis of the intermediate charnockite from Apelviken (No. 1 in Table III), representing a characteristic species of this group, and compare them with the Niggli values for the aplitic granite, there is naturally no coincidence whatever. But if as an experiment we add the values as given below and halve the totals, the Niggli values of the hybrid rock are found to be all but identical with the means thus found.

Naturally one should not draw exaggerated conclusions from these figures. But when the specimen of a hybrid rock singled out for analysis both megascopically and under the microscope indicates about a half and half intermixture of the components given below, the figures become more significant and might corroborate

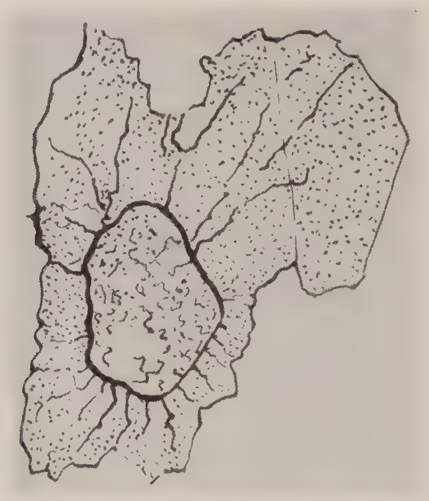

Fig. 19. Large zircon enclosed in apatite (dotted). × 130. Bankahalla, Träslövsläge.

the assumption gained in the field that many of the hybrid rocks are the result of the aplitic granite penetrating rocks of intermediate charnockitic composition. As the intermediate rocks themselves are assumed to be of synthetic origin (cf. p. 312), the megascopically hybrid rocks would represent a "hybridism of a second order" according to HARKER's terminology.[1]

	si	*al*	*fm*	*c*	*alk*	*k*	*c/fm*
intermediate charnockite .	168.8	29.5	30.7	19.6	20.2	0.37	0.64
aplite granite	421.6	48.8	9.3	6.5	38.4	0.65	0.70
	590.4	75.3	40.0	26.1	58.6	1.02	1.34
mean values	295.2	37.7	20.0	13.0	29.3	0.51	0.67
Niggli values for hybrid rock	301.4	39.0	19.3	12.2	29.5	0.56	0.63
difference	+6.2	+1.3	−0.7	−0.8	+0.2	+0.05	−0.04

The rocks of the surrounding gneiss formation

The so-called iron-gneiss formation of SW Sweden is a very uniform and characteristic rock complex over large areas. Its development in the Varberg district where it surrounds the charnockitic rocks, is in no way dissimilar to the normal appearance of the gneiss in other regions. A striking example of uniformity also in chemical composition is seen in the two analyses in Table V. The one (No. 1) is from near the contact with the charnockites, the other (1A) is from a locality quite 80 km distant. The two analyses, as well as Niggli values and norms, are all but identical.

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[1] The tertiary igneous rocks of Skye, p. 196.

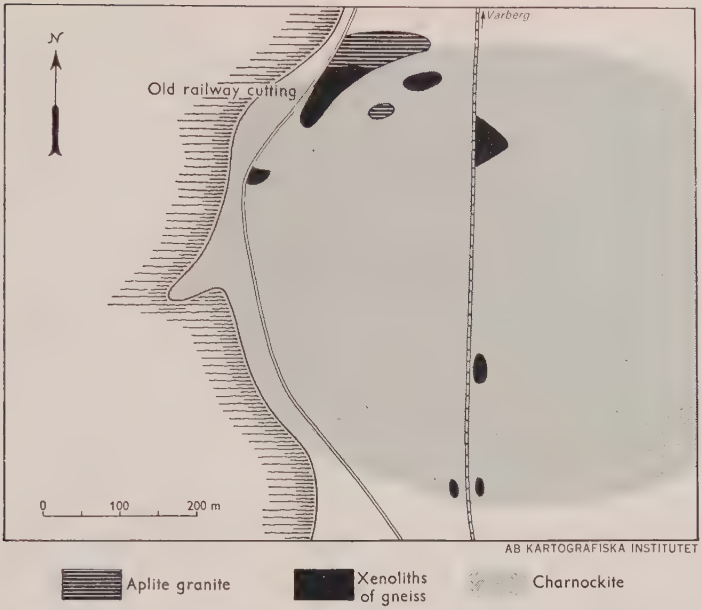


Fig. 20. Xenoliths of gneiss in intermediate charnockite. Old railway cutting south of Varberg.

A short description of the gneiss has already been given under the heading 'Distribution and mode of occurrence' (p. 233). As to the general appearance of these rocks there is little to add. Within the Varberg district the appearance of the gneiss is much the same in all directions away from the charnockitic area. The mineral composition is quartz, microcline, often developed as microcline-perthite, plagioclase (oligoclase), biotite, an often much decomposed greenish hornblende, stray grains of garnet and as accessory minerals abundant zircon and magnetite.

In general the contact between the gneiss and the charnockitic rocks is singularly sharp without signs of reaction. A good example is found on the island of Bondeholmen. At some other contacts a slight modification can, however, sometimes be observed in the form of a more massive texture. This is still more evident in some large xenoliths of gneiss within the charnockite rocks which are found in several places. Some significant localities are the southern wall of the quarry at Fästningsberget, the old railway-cutting south of Varberg (Fig. 20), the central part of Getterö island, and by the old mill near Trönningenäs.

In all these places the xenoliths have very much the same outward appearance. The gneiss has lost its characteristic reddish colour and is now brownish-gray. At the same time the texture has become more massive and relatively more coarse-grained.

The mineral composition of the xenoliths is much the same in all the occurrences mentioned. The felspars are microcline and microcline-perthite (often cryptoperthitic), plagioclase (about Ab 70, An 30), biotite and hornblende. The hornblende is of a more bluish-green colour than in the surrounding gneiss, with X yellowish-green, Y bluish-green and Z greenish-blue. The extinction x/Z is about 14°. Garnet is present in small grains or droplike in form. It is almost colourless, in contrast to

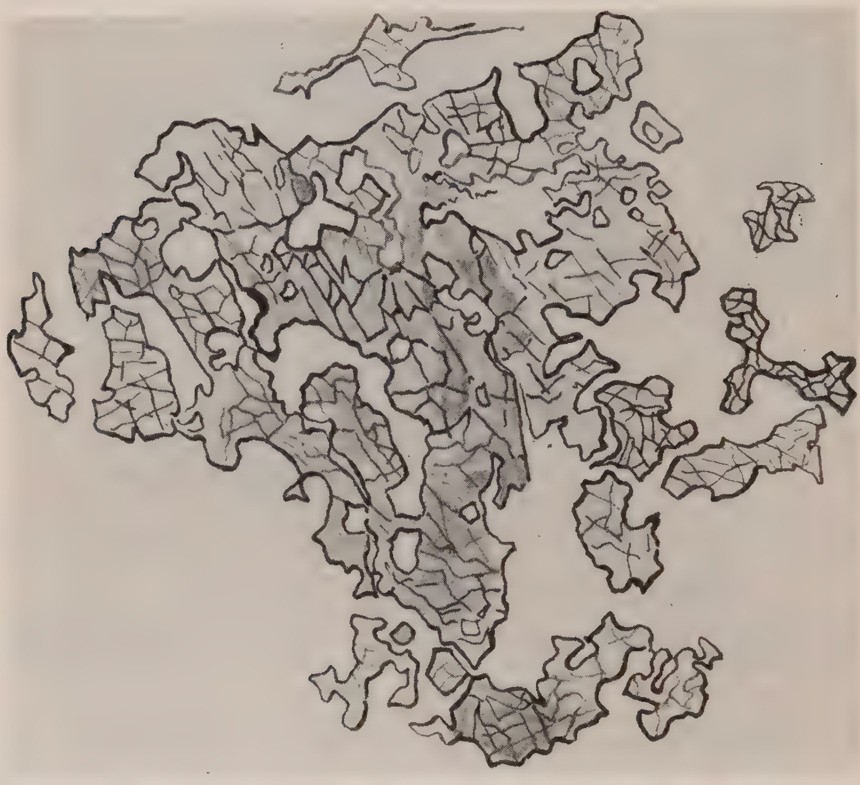


Fig. 21. Garnet in stage of disintegration. ×70. Påskberget, Varberg.

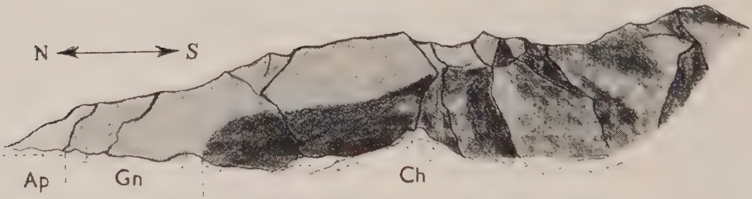
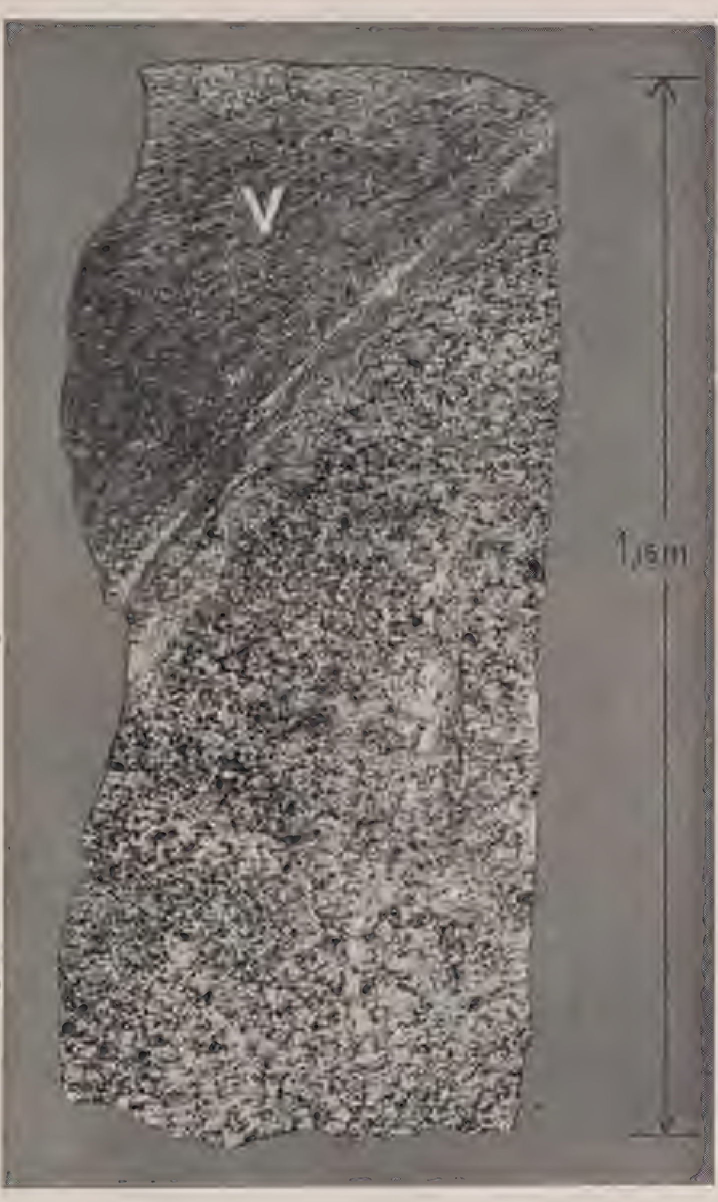


Fig. 22. Xenolith of gneiss in contact with aplite granite and intermediate charnockite. Old railway cutting south of Varberg town. Scale 1 : 300.
Ap = aplite granite. Gn = gneiss. Ch = charnockite.

the garnets in many of the charnockitic rocks. Biotite, garnet and hornblende have a pronounced tendency to cluster together in small agglomerations. In specimens from the old mill at Trönningenäs the microcline-perthite is very coarse, with the components of the intergrowth occurring in about the same quantities.

An occurrence of probably the same nature, but with a somewhat different aspect, is found at Påskberget in the eastern part of Varberg town. There the rock is of a more bluish colour than in the xenoliths from the other localities. The felspars are no longer perthitically developed. The colourless garnets are present in larger but very much corroded individuals (Fig. 21). Stray grains of much decomposed py-



Zone of assimilation

Fig. 23. Contact between granulose intermediate charnockite (V) and a large xenolith of the surrounding gneiss. Away from the contact an expanse of about 3 cm in the figure shows signs of assimilation, where the light red gneiss has assumed a greenish shade. Old railway cutting south of Varberg.

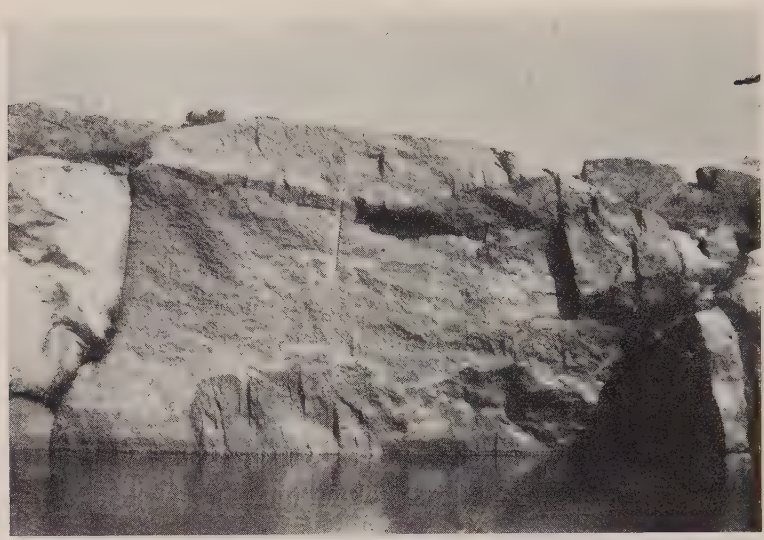


Fig. 24. Inclusions of amphibolite in the hybrid rocks of Fladahalla quarry. Träslövsläge. In the upper part an elongated inclusion. Lower down a large irregular xenolith.

roxenes occur. Their nature could not, however, be determined as no fresh parts remain. A brownish-green hornblende probably represents relics of the original mineral association of the gneiss. Another hornblende of a definite bluish colour evidently belongs to a later stage of metamorphism. One gets the impression that this rock may represent a more fenitic stage of alteration, during which the xenolith has assimilated a certain content of charnockitic material.

In the old railway-cutting south of Varberg town a xenolith of gneiss is found in contact both with the aplite granite and with intermediate charnockite (Fig. 22). It is of interest to note that no change whatever has been brought about by the aplitic granite. In that direction the gneiss has retained its normal aspect in every way. Against the intermediate charnockite, on the other hand, the gneiss shows a zone, about 3 dm in width, of a distinctly greenish tinge, indicating a certain amount of assimilation between the two rocks (Fig. 23).

The many textural and mineralogical features which most of the xenoliths have in common are probably due to similar conversions. These must be placed in connection with thermal-metamorphic processes of a wholly different character from the pluto-metamorphic evolution of the charnockitic rocks.

The basic components of the country rock surrounding the Varberg charnockite region consist of what Svedmark has named 'diorite schists' in his description of the Survey map and of amphibolites. As already noted, the latter, more insignificant in distribution, have not been indicated on Svedmark's map.

The dioritic, or rather gabbroic, rocks of the surrounding formation are of somewhat varying appearance. An analysed rock of this category from Ullered, over 20 km inland and therefore well outside the charnockitic area, can be taken as a general representative of the group. Quartz is present only in small particles in

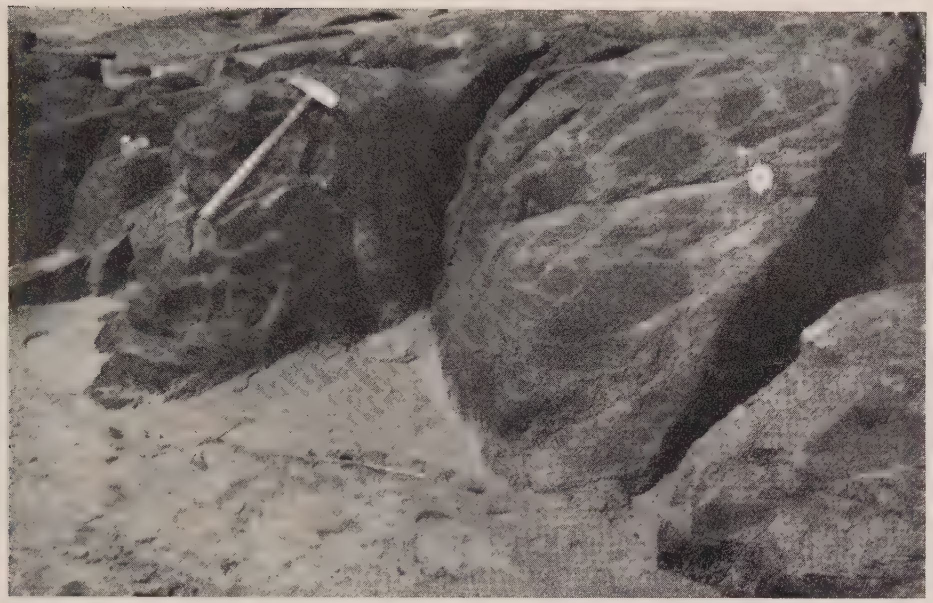


Fig. 25. Rounded inclusions of amphibolite in intermediate charnockite. The amphibolite shows indications of beginning charnockitisation. Apelviken bathing-shore south of Varberg.

connection with mineral decomposition. The predominating felspar is andesine (Ab 60, An 40). A brownish-green hornblende is abundant and of much the same appearance as in those basic charnockites which still contain a more or less high content of hornblende. A light green augite is found only as stray particles, surrounded and encroached by hornblende. Stray grains of a colourless garnet are generally present.

Rocks from other inland occurrences exhibit much the same mineral composition. In specimens from Okome, augite occurs in fairly large individuals along with light pink garnets, whereas similar rocks from Velasjö are devoid of any pyroxene mineral. In rocks from Norra Härta, augite is abundant in every stage of uralitisation. In this locality garnet may be plentiful in one specimen but lacking in another.

With regard to petrographic classification, all the rocks now described, belonging to the basic rocks of the surrounding area, represent somewhat varying types of gabbroic composition in different stages of uralitisation.

Besides these rocks there occur what may be termed true amphibolites, interfoliated in the gneiss complex and synchronised with the metamorphic evolution of this formation (Fig. 24). These rocks have in all respects the normal composition of other amphibolitic rocks in similar environments. They mostly show variations in respect of the content of garnets, which may be abundant or wholly absent.

An interesting small occurrence is found exposed on the bathing-beach of Apelviken, just south of Varberg town. Incidentally it was this exposure that first directed my interest to the problems of the district. In intermediate charnockite of normal appearance are to be seen small rounded inclusions of a dark amphibolitic rock (Fig. 25). Under the microscope this rock at first sight shows a normal amphibolitic aspect. Hornblende, garnet and plagioclase are the principal mineral constituents. However, in some thin sections one may observe diopside particles, encircled by a rim of hypersthene in striking resemblance to what has been found in some of the basic charnockites. In this case the inclusions in the intermediate charnockite, by chance exposed in some isolated flags, would then represent a commencing charnockitisation of an amphibolitic rock.

In Table V analyses of a gabbroic rock and of an amphibolite are given for comparison with the basic charnockites in respect of chemical composition. This subject is treated in detail under a later heading (p. 283).

Rocks of an uncommon aspect, not otherwise represented within the Varberg district, are found on the north-eastern part of the island of Getterö and by the railway-crossing at Lassabacka. Megascopically they have the aspect of a highly garnetiferous amphibolite.

On Getterö the occurrence of these rocks forms a continuous and well defined ridge, striking SE — NW from further inland to the northern promontory of the island, about 3/4 km in length. In the SE parts the rocks are more fine-grained than northwards, where near the shore they ultimately develop into very coarse-grained rocks, closely set with large garnets, attaining to over 1 1/2 cm in diameter. In places they can, in uniform distribution, form up to 50% of the rock constituents (Fig. 26).

The singular appearance of this rock, with garnets of this magnitude, is further accentuated by the circumstance that each garnet individual is surrounded by a border zone of pure white plagioclase, 1 to 2 mm in width.

Table V.

Analyses of rocks from the surrounding gneiss complex.

	1	1 A	2	3	4
SiO_2	70.92	70.46	45.56	46.52	46.28
TiO_2	0.32	0.79	0.36	1.50	2.40
Al_2O_3	13.88	13.97	18.63	16.07	13.67
Fe_2O_3	1.61	3.02	2.47	7.66	3.34
FeO	1.23	0.72	4.79	6.78	12.80
MnO	0.10	0.38	0.12	0.40	0.14
MgO	0.51	0.57	10.64	6.32	6.86
CaO	1.48	1.42	12.10	8.60	10.56
Na_2O	2.88	2.93	2.71	2.76	0.68
K_2O	6.25	5.68	1.67	3.54	2.48
P_2O_5	trace	—	0.00	0.00	trace
$H_2O^{-105^\circ}$	0.05	—	0.02	0.13	0.24
$H_2O^{+105^\circ}$	0.44	0.51	0.96	0.11	0.14
	99.67	100.45	100.03	100.39	99.59
Sp. gr.	2.63		3.03	3.02	3.18

1. Orthogneiss from the surrounding formation. South of Träslövsläge.
1 A. Typical gneiss from a central part of the gneiss formation of SW Sweden. E of Lake Töllesjö, NW of Borås.
2. Uralitic gabbro, Ullared station.
3. Amphibolite, Bankahalla, Träslövsläge.
4. Garnetiferous amphibolite. North shore of Getterö Island.

Table V (cont.).

	1	1 A	2	3	4
Niggli Values:					
si	363.4	347	92.1	103.9	102.5
qz	125.4	119	−37.9	−40.1	−17.5
al	41.8	40.5	22.2	21.1	17.9
fm	15.7	20	44.1	47.3	52.1
c	8.0	7.5	26.2	20.6	25.0
alk	34.5	32	7.5	11.0	5.0
k	0.59	0.56	0.29	0.46	0.71
c/fm	0.51	0.37	0.59	0.43	0.48
Norms:					
Q	26.22	27.80	—	—	—
or	36.96	33.56	9.85	20.93	14.64
ab	24.38	24.80	3.22	12.74	5.77
an	6.48	7.04	33.76	20.99	26.92
ne	—	—	10.67	5.74	—
di	0.70	—	20.89	17.27	21.03
hy	1.52	1.42	—	—	16.03
ol	—	—	16.38	8.52	5.64
il	0.61	1.50	0.68	2.84	4.55
mt	2.34	1.27	3.59	11.11	4.84
sal.	94.04	93.62	57.50	60.40	47.33
fem.	5.17	6.33	41.54	39.74	52.09

1.	I : 4 : 2 : 3	Toscanose	or : ab : an	54.50 : 35.95 : 9.55
1 A.	I : 4 : 2 : 3	Toscanose	or : ab : an	51.32 : 37.92 : 10.76
2.	III : 5 : 4 : 4	Auvergnose	or : ab : an	21.03 : 6.88 : 72.09
3.	III : 5 : 3 : 3	Kentallenose	or : ab : an	38.29 : 23.31 : 38.40
4.	III : 5 : 4 : 2	(sodipotassic)	or : ab : an	30.93 : 12.19 : 56.88

The predominating interest under the microscope is concentrated on the garnets and their reaction zones. The plagioclase encircling the garnets is an andesine of the composition Ab 60, An 40. The small individuals, mostly twinned after (101), are not crystallographically orientated though a certain tendency can sometimes be observed towards an adjustment of the c-axis vertical to the zone (Figs. 27 and 28). An outer zone round the garnets, when present, consists of a light green diopside of the same character as in the charnockitic rocks of the district.

The large garnets often contain a circular cluster of felspar microlites in their centres. Their radial extension is generally up to 2/3 of the diameter of the garnet, the remaining 1/3 then being free from inclusions.

The finer-grained rocks south-eastward are directly connected in the field with the type described. The only difference is that the garnets are not developed as such large porphyroblasts but are not therefore less abundant, being uniformly dispersed throughout the rock in smallish grains.

It is of a certain genetical interest to note that rocks of the same character in the other locality, Lassabacka, there occur in close connection with the typical analysed basic charnockite of the same locality. Here too, large garnets of up to 1/2 cm in diameter are surrounded by an inner ring of plagioclase and an outer ring of diopside, of identically the same appearance as those in the rocks at Getterö.

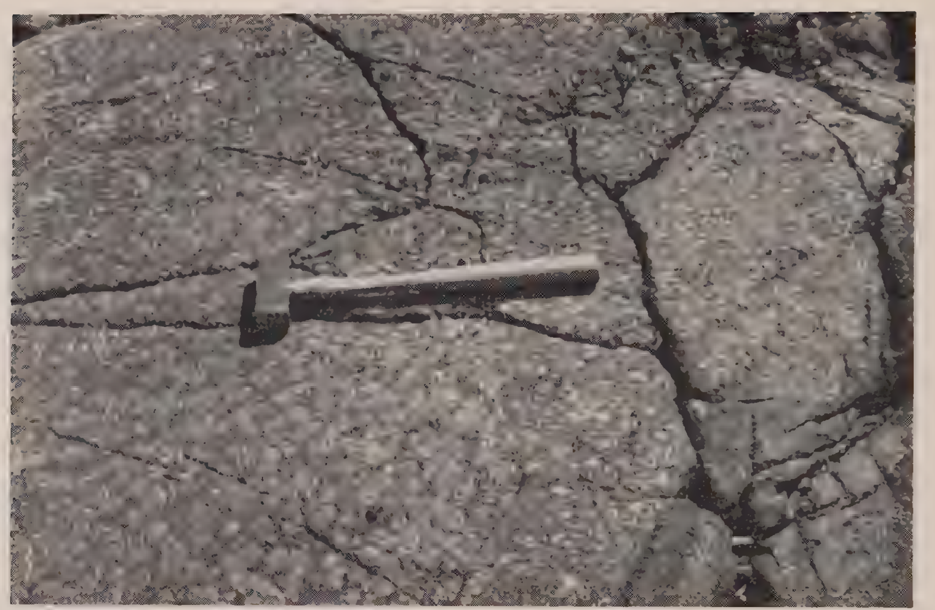


Fig. 26. Garnetiferous amphibolite. Northern promontory of Gettero island.

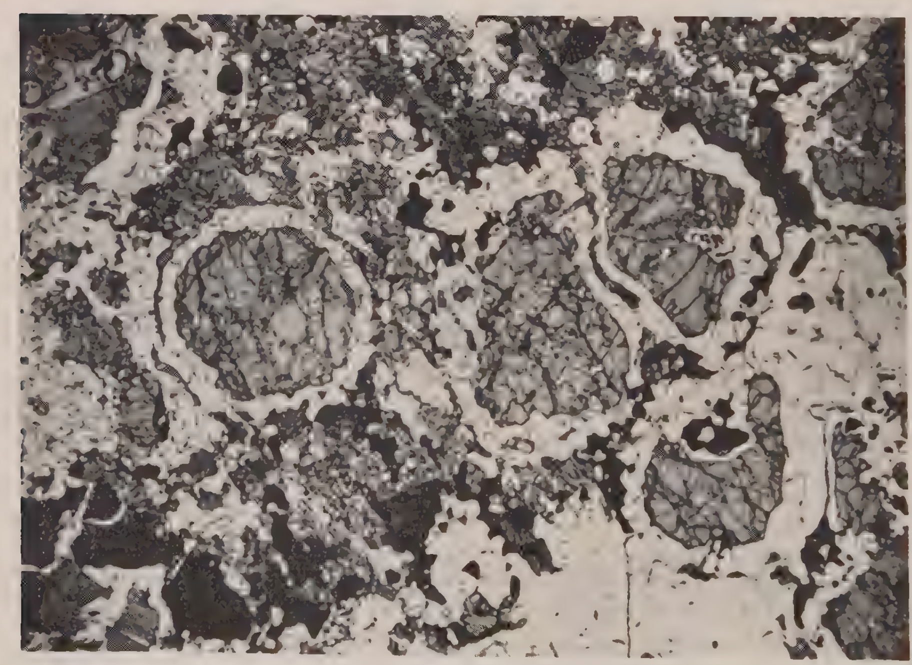


Fig. 27. Garnetiferous amphibolite. Large garnets with reaction rims of plagioclase and diopside denoting an incipient charnockitisation. × 9. Same locality as Fig. 26.

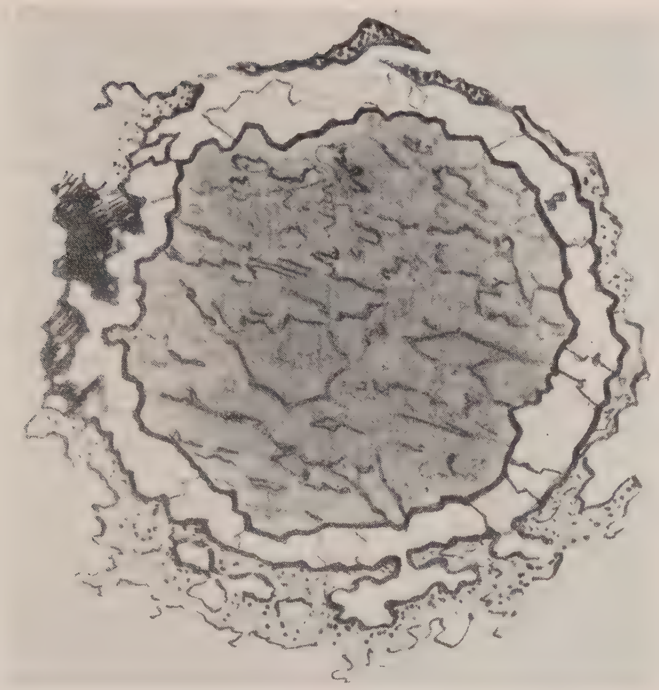


Fig. 28. Large garnet from Fig. 27. Inner reaction rim of plagioclase (white), outer rim diopside (dotted), residual flakes of hornblende (black). × 20. Getterö island.

Apart from the garnets and their reaction zones, the minerals in all these rocks consist of plagioclase, hornblende and pyroxene, in many cases forming only a matrix between the large garnet porphyroblasts. The pyroxenes offer aspects of special interest. Whereas the pyroxene forming the outer ring of the reaction zones round the garnet is distinctly a diopside, the nature of the remaining rock-forming pyroxenes is more difficult to define.

The usual optical determinations do not in this case suffice to determine the species, as the optical constants for a diopside with c. 40% hedenbergite molecules are almost identical with those for a normal augite. Another feature may, however, afford some conclusions. This is that the pyroxenes outside the reaction zones do not in general show any definite extinction between crossed nicols. One gets the impression that they are not uniform in their structure. They might then represent an intermediate stage during a gradual conversion from augite to diopside. Such a conversion has without doubt taken place in the charnockite rocks and has there attained completion. In the case of the rocks from Getterö and Lassabacka one might surmise that the conversion of augite into diopside has been interrupted before a structural equilibrium was reached. Dr. O. Mellis of this Institute kindly attempted to determine the optical constants of the pyroxenes of the Getterö-Lassabacka rocks on the universal stage. The results support the conclusions indicated above.

All observations point to the conclusion that the rocks in question have been dykes, transversing the old gneiss complex. The dyke at Getterö can, as already mentioned, be followed for 3/4 km, the width varying between 20 and 40 m. Before its epoch of partial amphibolitisation it in all probability was a doleritic sheet or dyke. In connection with later more deep-seated metamorphism it succumbed to an initial charnockitisation. It is probable that the rocks, previously to this metamorphic process, were garnetiferous and that the garnets grew in size during a later metamorphic period. The striking reaction rings of plagioclase and diopside must be referred to a concluding stage of the evolution.

At Lassabacka the charnockitisation has in part evidently gone further, resulting in the formation of typical basic charnockites free from all hornblende. It is remarkable how close the boundary is between the rocks representing a commencing charnockitisation of an amphibolite and true basic charnockites. Probably a subsequent dislocation has to some extent obliterated the primary metamorphic connection.

An analysis of the coarse-grained garnetiferous amphibolite from the northernmost promontory of Getterö is given in Table V, No. 4.

Although I hesitate to accept the hypersthene-bearing rocks of the Bergen field in Norway as belonging to the charnockite series in accordance with Holland's precise definition, as used in this paper, I cannot abstain from referring to Fig. 76 and 77 in C. F. KOLDERUP's description of the labradorites from Hagasaeter in Storsnuten. The two figures might equally well refer to the Getterö rocks. The felspar ring round the garnets in Fig. 77 is apparently identical with what has been described above. Here, however, this reaction phase must have taken place under different metamorphic conditions. Kolderup called the rock a "basic separation" in a labradorite rock. (Bergens Museum Aarbok 1914—15, p. 160, English summary, p. 241).

The significance of the mineral composition in respect of the origin of the Varberg charnockite series

With regard to the characteristic mineral composition of all rocks of the charnockitic series, which can be regarded as typical representatives of this petrographical group, two essential features have repeatedly been emphasized. The one is the divergence in many essential respects of the minerals of the charnockites within a certain charnockitic area, in respect of the mineral composition of the rocks in the surrounding territory, indicating an independent evolution of the charnockitic rocks, in which the rock formations apart have not been involved. The other characteristic feature is the association of dry minerals of high density and small specific volume, indicating that they were formed under conditions of great uniform pressure and high temperature. Irrespective of the origin of the rocks, the ultimate crystallisation of the minerals would thus have been subjected to conditions regulated by what of late has been designated plutonic metamorphism.

The association of the minerals, characteristic of most typical charnockitic rocks of the Varberg district, has already been treated, and the individual minerals described. In these respects there is not much to add. In those rocks where, if I may so express it, the charnockitisation has culminated, the most characteristic minerals are antiperthite, a relatively acid plagioclase, hypersthene, diopside, garnet and ore minerals.

I shall first refer to the significance of antiperthite in the charnockitic rocks.

Though in no way restricted to the charnockites, the antiperthitic development of the felspars is of general occurrence there, as has been indicated by many investigators in the subject. In many cases in the basic charnockites all the potassic felspar occurs as a constituent of antiperthite. It readily suggests itself to assume an unmixing of a primary homogeneous felspar, the rocks having been held for a long period at temperatures appropriate for unmixing. This might, as TILLEY expresses it, "be accounted for by consolidation of a dry magma, crystallisation being arrested at a high temperature due to the paucity of water in the magma". (Tilley, B A. N. Z. p. 16.).

A question not previously treated concerns observations on the reactions between the minerals in the charnockites of the Varberg district and the conclusions which may be drawn therefrom relating to the mineral sequence and to the origin and general metamorphic evolution of the rocks.

An extensive literature by different authors exists on the subject of reaction series between the minerals of the charnockitic rocks, based both on microscopical study and on more theoretical argumentation. As regards the charnockitic areas of Peninsular India, I may mention HOLLAND, GHOSH, RAMA RAO and GUPTA. Their discussions on the subject are especially devoted to the series diopside — hypersthene — garnet with acidisation of plagioclase and formation of secondary quartz in connection with the reactions (Holland 1896, p. 20, Gupta, p. 123, Rama Rao, p. 93, Ghosh, p. 19.).

GROVES has also discussed the subject in detail in his paper on the Uganda charnockites. His arguments are of special interest, as they are not only based on microscopical studies but are furthermore corroborated by chemical analyses of the minerals in question. He also goes a step further, including both biotite and hornblende as primary minerals, preceding the diopside-hypersthene reaction series as the result of a later re-mineralisation (Groves, p. 196.). From a theoretical point of view, RAMBERG has given an interesting outline of different possible reactions within the mineral groups in question (Ramberg, 1948, p. 558.).

In the basic charnockites of the Varberg district, the conversion of a greenish-brown hornblende into diopside is obvious in many of the types which contain hornblende more or less plentifully. In different sections one can observe all stages represented, from an incipient encroachment of hornblende by diopside to residual traces of hornblende in diopside. In all probability this hornblende is in many cases residual uralite from the metagabbros or metabasites of the surrounding gneiss formation, which were exposed to an earlier period of metamorphism, preceding the metamorphism of the charnockitic rocks.

In contrast to what Groves has written regarding the basic charnockites of Uganda, the equigranular minerals of the basic charnockites in the Varberg district show nothing of the well defined reaction rims or kelyphitic borders, interpreted by Groves as "modifications due to dynamic metamorphism" (Groves, p. 183). Reactions of this sort are entirely absent, as this metamorphic stage has not been active within the Varberg charnockitic area.

Observations of interest with regard to the mineral sequence in the basic charnockites are, apart from the hornblende, restricted to the pyroxenes. As already noted, hypersthene is in most cases found to fringe larger diopside individuals in the form of small unorientated granular grains, obviously indicating a definite sequence diopside hypersthene. The garnets occur in rounded grains, without any signs of reactions with other minerals.

The pronounced poikiloblastic development of the pyroxenes may again be worthy of notice. Large diopside crystals are often so riddled with felspar that only traces of the pyroxene remain. In another case hypersthene is seen dispersed as strings of orientated grains within what probably was a single individual. Here too one may assume a poikiloblastic texture, where the felspar chadacrysts completely preponderate over the oikocrysts, resulting in a perchadic fabric, wherein the hypersthene constitutes only sparse interstitial grains between the chadacrysts.

In general, however, one may say that the basic charnockites show but few traces of subsequent reactions between the constituent minerals.

Rocks of the intermediate division likewise show few traces of specific reactions due to later conversion. Features of significance are in most cases restricted to the mutual relationship between the monoclinic and the orthorhombic pyroxenes and to the development of the garnets.

Whereas in the basic rocks the diopside was in most cases fringed with reaction borders of granular hypersthene, in the intermediate types we generally find diopside enveloped by an orientated outer zone of hypersthene. In some specimens the ring of hypersthene is merely a narrow fringe, in others the diopside is almost entirely consumed, leaving only some stray remnants in the central parts. The hypersthene is of a different character from that of the basic rocks, being only faintly pleochroic, and more liable to decomposition into serpentine. A fresh central part of diopside may be surrounded by an outward zone of more or less decomposed hypersthene.

In the sub-acid charnockites of the district, however, we often meet with the reverse relation. Large uniform crystals of a now again highly pleochroic hypersthene of the same type as that of the basic charnockites are surrounded by a uniform crystal of diopside. The hypersthene forms well rounded grains, indicating a symmetrical encroachment of diopside during a process of de-hypersthenisation.

A further item of interest in this connection concerns the garnets. In the basic rocks the garnets were always bright pink in colour and developed in rounded grains with well defined circumferential boundaries. In most of the rocks of the intermediate charnockites the garnets are completely colourless and show deeply corroded borders. In some cases only a skeleton framework of an original grain survives, in other cases an originally larger garnet is found dispersed in an aggregation of small grains. In the leucocratic schlieren of rocks from Trönningenäs the garnets are sometimes corroded, sometimes dispersed in clusters (cf. Fig. 15). In most of the intermediate charnockites the garnets in large crystals are riddled with small felspar inclusions. The same is often the case with the hornblende, whereas the pyroxenes are generally now free from inclusions.

Though, on the whole, the normal charnockites of the Varberg series do not show much of the significant reactions described from so many other localities of charnockitic rocks, we may however draw certain conclusions regarding the sequence of ultimate crystallisation.

In the basic charnockites the sequence of mineralogical reconstruction seems definitely to be

$$\begin{tikzcd} & & \text{hypersthene} \\ \text{hornblende} \arrow[r] & \text{diopside} \arrow[ur] \arrow[dr] & \\ & & \text{garnet} \end{tikzcd}$$

The transformation of hornblende into diopside will be connected with absorption of Ca, presumably taken from the more basic plagioclase of a primary gabbroic rock. This would result in an acidification of the plagioclase and explain the presence of so acid a plagioclase in the basic charnockites (usually about An_{35}).

The reactions from diopside to hypersthene and garnet in the basic charnockites have probably followed more than one reaction series, as no indications are found pointing to anything other than a synchronic formation of these minerals. The reactions may have proceeded in one or two such changes as

diopside + acid plagioclase → hypersthene + garnet + quartz
diopside + basic plagioclase → hypersthene + garnet + acid plagioclase + quartz

or simply diopside + plagioclase → garnet.

The amount of uniformly distributed garnet in these rocks, in the same equidimensional grains as the pyroxenes, makes it probable that several modes of reaction have taken place more or less simultaneously. The presence of secondary quartz (though Niggli values of *qz* are negative) indicates a participation of the two first reactions which, owing to continued acidification of the plagioclase would, furthermore, explain their acid character in the rock in question. Much the same, or identical, reactions have been suggested by Groves, Ghosh and Ramberg.

In the intermediate charnockites one may often observe — apart from a primary set of reactions of nature similar to those in the basic charnockites — reactions of a reverse order. The hypersthene individuals become much corroded, locally resulting in a dispersed lot of small grains, or else large corroded hypersthenes become enveloped by diopside. The same is the case with the garnets. One finds every stage, from deeply corroded grains to a dispersion in small drop-like particles. It seems probable that, in the intermediate rocks and perhaps especially in the sub-acid varieties, conditions have changed since the first crystallisation, giving rise to a retrograde reaction series. This is then often accompanied by the formation of a new hornblende of a distinctly more bluish tinge. The reversed reaction series would then be

$$\begin{tikzcd}
\text{hypersthene} \arrow[dr] & & \\
& \text{diopside} \arrow[r] & \text{bluish hornblende} \\
\text{garnet} \arrow[ur] & &
\end{tikzcd}$$

or exactly the opposite of the reaction indicated above. In this case transformations may have been accelerated by a certain volatile influx in connection with assimilation through the agency of the aplitic granite. Stray grains of scapolite point to the same explanation.

In some types where biotite occurs more plentifully, one may presume that reactions have continued to a further stage, involving a break-down of hypersthene through intermediate stages of diopside and hornblende to biotite. Under the influence of a highly alkaline fluid, hypersthene would become unstable. Ghosh surmises that such a process of 'de-hypersthenisation' was responsible for the transition of a charnockitic hypersthene granite into diopside granite and then into an aplitic granite (Ghosh, p. 52). In many intermediate charnockites in the Varberg area the successive disappearance of hypersthene and diopside in connection with the formation of a more bluish hornblende may indicate such an ultimate stage of retrogaded metamorphism. A new-formed biotite may then represent a final metamorphic stage.

The simpler mineral composition of the felsic charnockites, devoid of both pyroxenes and garnet, do not afford any indications of reactions between the rock components. The same is naturally the case with the aplitic granite.

The significance of the chemical composition in respect of the origin of the Varberg charnockites

The chemical composition of rocks belonging to the charnockite series has been a subject of interest to all authors dealing with this problem. New analytical data have been compared with analyses from other occurrences of charnockite rocks, and analogies have been sought and to a certain extent proved.

To begin with I also tried to anticipate some characteristic features in chemical composition between the Varberg series and charnockites from other regions. 31 analyses of rocks which could be taken as definitely representing the most typical representatives of the charnockite series were re-calculated in a similar way, and norms and Niggli values were calculated. These analyses included 6 from Madras (new analyses by Washington from Holland's original localities), 5 from Mysore

Table VI.

Comparison between the chemical composition of the surrounding gneiss and chemically corresponding charnockitic rocks within the Varberg area and from Uganda.

	1	2	3	4
SiO_2	72.32	70.92	64.64	60.45
TiO_2	0.16	0.32	0.72	1.50
Al_2O_3	14.46	13.88	14.73	17.56
Fe_2O_3	1.24	1.61	1.77	0.62
FeO	0.67	1.23	4.55	5.77
MnO	0.02	0.10	0.08	0.10
MgO	0.33	0.51	1.72	1.60
CaO	1.78	1.48	4.13	4.72
BaO	—	—	0.11	0.18
Na_2O	3.39	2.88	3.25	3.75
K_2O	4.92	6.25	3.19	2.45
P_2O_5	0.00	trace	0.40	0.31
ZrO_2	—	—	—	0.01
S	—	—	0.08	0.09
$H_2O^{-105°}$	0.34	0.05	0.03	0.53
$H_2O^{+105°}$	0.50	0.44	0.74	0.75
			100.14	100.39
O for S			0.03	0.03
	100.13	99.67	100.11	100.36
Sp. gr.	2.66	2.63		2.72

1. Felsic charnockite, Himle. (Table IV, No. 2.)
2. Gneiss of the surrounding formation.
3. Typical orthogneiss surrounding the charnockite mass of Mt Wati, Uganda.
4. Intermediate charnockite, Mt. Wati, Uganda.

Table VI (cont.).

	1	2	3	4
Niggli Values:				
si	383.7	363.1	247.7	212.7
qz	147.3	125.4	68.1	39.5
al	45.2	41.8	33.3	36.4
fm	10.6	15.7	29.7	27.3
c	10.1	8.0	17.1	18.0
alk	34.1	34.1	19.9	18.3
k	0.49	0.49	0.39	0.30
c/fm	0.95	0.51	0.57	0.66
Norms:				
Q	29.50	26.22	20.97	13.88
or	29.05	36.96	18.87	15.01
ab	28.68	24.38	27.47	31.44
an	8.84	6.48	16.19	21.78
C	0.33	—	—	0.64
di	—	0.70	1.58	—
hy	0.82	1.52	9.21	11.66
il	0.30	0.61	1.37	2.89
mt	1.76	2.34	2.57	0.93
hm	0.03	—	—	—
ap	—	—	0.94	0.67
pr	—	—	0.11	—
sal.	96.40	94.04	83.50	82.75
fem.	2.91	5.17	15.78	16.15

1.	I : 4 : 2 : 3	Toscanose	or : ab : an	43.64 : 43.08 : 13.28
2.	I : 4 : 2 : 3	Toscanose	or : ab : an	54.50 : 35.95 : 9.55
3.	I : 4 : 3 : 3 (4)	Amiatose	or : ab : an	30.18 : 43.93 : 25.89
4.	II : 4 : 3 : 4	Tonalose	or : ab : an	22.00 : 46.07 : 31.93

(Rama Rao), 8 from Ceylon (Adams), 3 from Uganda (Groves), 3 from Ivory Coast (Lacroix), 4 from Arendal, Norway (Jens Bugge) and 2 from Enderby Land (Tilley).

These analyses, together with 7 analyses of the Varberg series, were plotted in different diagrammatic projections (Fig. 29 –34). The result was found to be that a series of analyses from one region could well be taken to represent a certain petrographic type. More or less well defined similarities in general chemical composition could also be discerned in relation to other districts, but marked differences were equally obvious. This has occasioned the many local names given to different rocks and rock series of the charnockites: Akafoamite and Ivoirite (SCHÜLLER), Arendalite (J. BUGGE), Enderbite (TILLEY), Bugite, Epibugite, Katabugite, and Sabarovite (BEZBORODBO). The differences have been ascribed mainly to variations in the proportions of K: Na: Ca in combination with differences in the acidity of the rocks.

One finds, furthermore, that there is no difficulty in choosing analyses of normal igneous rocks which in any diagrammatic projection fully coincide with the position calculated from analyses of rocks of typical charnockitic composition. As already mentioned, in his original paper on the charnockite series Holland anticipated this fact. I again cite his own words on this point: "The terms used for varieties within the group are those used for mineralogically similar igneous rocks. · · · Thus the types which are composed essentially of hypersthene and plagioclase are norites and, all according to the ferro-magnesian silicate associated with the rhombic pyroxene we may have augite-norites, hornblende-norites and mica-norites."

Groves calls the acid type of the charnockite series of Uganda hypersthene-granite, the intermediate types quartz-hypersthene-diorite and the basic types norites of different subdivisions. Jens Bugge gives the rocks of the Arendal charnockite series the collective name arendalites and distinguishes within his acid group (with over 65% SiO_2) quartz-hypersthene-granites, hornblende-granites and biotite-granites. Within the intermediate group (55—65% SiO_2) he uses the names quartz-norites, quartz-hypersthene-diorites, and rocks of mangeritic or monzonitic composition. In the basic series (48—55% SiO_2) he identifies the rocks petrographically as gabbros, norites, hornblende-norites and amphibolites.

I might continue with further quotations, but the above may suffice to show that as regards chemical composition the charnockite rocks in no way differ from normal igneous rocks in respect of petrographical classification. One may then ask what specific features distinguish the charnockite series from — in so many respects — equivalent igneous rocks.

Both from a theoretical point of view (TYRRELL, DUNN) and on the basis of detailed field work in Uganda and Peninsular India, the prevailing tendency is now to explain the origin of the charnockitic rocks as the result of a deep-seated metamorphic

Table VII.

Comparison between the chemical composition of the basic components within the surrounding gneiss formation and chemically corresponding basic charnockites within the Varberg area.

	1	2	3	4	5	6	7
SiO_2	44.60	45.00	45.56	46.52	46.28	48.30	50.17
TiO_2	5.12	2.40	0.36	1.50	2.40	0.93	1.54
Al_2O_3	14.36	16.62	18.63	16.07	13.67	18.01	15.58
Fe_2O_3	5.73	6.05	2.47	7.66	3.34	1.62	2.45
FeO	11.64	8.97	4.79	6.78	12.80	9.75	9.94
MnO	0.20	0.31	0.12	0.40	0.14	0.14	0.24
MgO	5.89	7.24	10.64	6.32	6.86	8.31	6.00
CaO	8.72	9.50	12.10	8.60	10.56	8.67	7.99
Na_2O	2.15	2.76	2.71	2.76	0.68	2.45	2.92
K_2O	1.37	0.96	1.67	3.54	2.48	0.76	0.84
P_2O_5	0.00	0.00	0.00	0.00	trace	0.18	0.28
S	—	—	—	—	—	0.06	0.15
$H_2O^{-105°}$	0.00	0.06	0.02	0.13	0.24	—	—
$H_2O^{+105°}$	0.14	0.16	0.96	0.11	0.14	1.02	1.75
	99.92	100.03	100.03	100.39	99.59	100.20	99.89
Sp. gr.	3.16	3.19	3.03	3.02	3.18	2.98	3.02

1. Basic charnockite, Lassabacka, Varberg.
2. Basic charnockite, Högahalla, Träslövsläge.
3. Uralite-gabbro, Ullared.
4. Amphibolite, Bankahalla, Träslövsläge.
5. Garnetiferous amphibolite, Getterö Island, Varberg.
6. Hyperite, Nyed, Värmland.
7. Hyperite–amphibolite, Nyed, Värmland (with BaO 0.04).

Table VII (cont.).

	1	2	3	4	5	6	7
Niggli Values:							
si	102.0	97.1	92.1	103.9	102.5	108.0	124.2
qz	−25.2	−31.3	−37.9	−40.1	−17.5	−18.0	−9.0
al	19.3	21.1	22.2	21.1	17.9	23.5	22.7
fm	52.6	49.8	44.1	47.3	52.1	49.0	47.8
c	21.3	22.0	26.2	20.6	25.0	21.0	21.2
alk	6.8	7.1	7.5	11.0	5.0	6.5	8.3
k	0.29	0.19	0.29	0.46	0.71	0.17	0.16
c/fm	0.41	0.44	0.59	0.43	0.48	0.43	0.44
Norms:							
Q	—	—	—	—	—	—	0.78
or	8.08	5.59	9.85	20.93	14.64	4.51	4.95
ab	18.19	22.25	3.22	12.74	5.77	20.71	24.70
an	25.50	30.07	33.76	20.99	26.92	35.90	26.92
ne	—	0.70	10.67	5.74	—	—	—
di	14.43	13.67	20.89	17.27	21.03	4.82	9.00
hy	13.83	—	—	—	16.03	15.19	24.32
ol	1.71	14.20	16.38	8.52	5.64	13.37	—
il	9.73	4.56	0.68	2.84	4.55	1.77	2.91
mt	8.31	8.77	3.59	11.11	4.84	2.34	3.54
pr	—	—	—	—	—	0.13	0.32
ap	—	—	—	—	—	0.44	0.67
sal.	51.77	58.61	57.50	60.40	47.33	61.12	57.35
fem.	48.01	41.20	41.54	39.74	52.09	38.06	40.76

1. III : 5 : 4 (3) : 4 Auvergnose or : ab : an 15.61 : 35.13 : 49.26
2. III : 5 : 4 : 4 Auvergnose or : ab : an 9.65 : 38.42 : 51.93
3. III : 5 : 4 : 4 Auvergnose or : ab : an 21.03 : 6.88 : 72.09
4. III : 5 : 3 : 3 Kentalenose or : ab : an 38.29 : 23.31 : 38.40
5. III : 5 : 4 : 2 (dopotassic) or : ab : an 30.93 : 12.19 : 56.88
6. III : 5 : 4 : 4 Auvergnose or : ab : an 7.38 : 33.88 : 58.74
7. III : 5 : (3) 4 : 4 Auvergnose or : ab : an 8.76 : 43.65 : 47.59

evolution. Groves, Vredenburg, and Rama Rao have perhaps most clearly expressed the opinion, based on extensive field observations, that the charnockitic series represents a metamorphic product, not of any special rocks, but of the whole rock basement in the parts where they occur. If this conception be accepted, we should have to look for the characteristic chemical composition of any local series of charnockitic rocks in the composition of the surrounding country rocks or their underlying basement.

In accordance with such an interpretation Groves has compared his analyses of the charnockite series of Uganda with several analyses made of the surrounding rocks. The analysis of a quartz-hypersthene-diorite of the intermediate division of the charnockite series is compared with that of a biotite-hornblende-tonalite-gneiss of the surrounding country rock. Groves says: "A very close similarity in chemical composition is manifest and is reflected equally well by both the major and minor constituents. The norms also agree closely and the specific gravities are almost identical". The analysis of the orthogneiss, plotted on a variation diagram with a chemically related type of the charnockitic rocks of the Uganda series, is said "to fit perfectly, five of the seven points being exactly on the curves, a sixth practically coincident and the alumina not farther out than the average. The chemical evidence leaves no doubt that the two rocks are both co-magmatic and heteromorphic" (Groves, p. 193).

The same relationship is assumed to exist between the chemical composition of certain types within the charnockite area of the Varberg district and the surrounding gneiss, the dominant country rock outside the charnockitic field. As, however, the gneiss is of a more acid composition than the most acid charnockites represented within the area, the closest chemical relationship with the surrounding gneiss must be sought in rocks belonging to the felsic charnockites. In Table VI the analyses of a felsic charnockite and of the surrounding gneiss have been reproduced and for comparison the two analyses from Uganda, on the basis of which Groves discusses the problem of their genetic relationship. For better comparison, the analyses of the gneisses are placed in the centre, flanked by the charnockitic rocks which correspond most closely in chemical composition. The gneiss from the Varberg district is seen to be essentially more acid than the corresponding gneiss from Uganda, which is reflected in the chemical composition of the most closely associated rocks in the two areas.

Table VIII.

Comparison between the chemical composition of a basic charnockite and basic rocks outside the charnockitic area in Uganda compared with analyses relating to the same problem within the Varberg area.

	1	2	3	4	5
SiO_2	47.00	49.70	49.97	44.60	46.28
TiO_2	0.69	1.05	1.32	5.10	2.40
Al_2O_3	15.59	14.30	10.94	14.36	13.67
Fe_2O_3	1.29	2.91	4.17	5.73	3.34
FeO	10.28	11.02	9.94	11.64	12.80
MnO	0.15	0.21	0.35	0.20	0.14
MgO	8.88	7.22	6.79	5.89	6.86
CaO	13.75	11.52	10.54	8.72	10.56
BaO	0.01	—	0.02	—	—
LiO	—	trace	trace	—	—
Na_2O	1.70	1.71	1.69	2.15	0.68
K_2O	0.07	0.18	2.26	1.37	2.48
P_2O_5	0.07	0.24	0.31	0.00	trace
S	trace	0.05	—	—	—
$H_2O^{-105^\circ}$	0.14	0.02	0.09	0.00	0.24
$H_2O^{+105^\circ}$	0.40	0.30	1.52	0.14	0.14
		100.43			
O for S		0.02			
	100.02	100.41	99.91	99.92	99.59
Sp. gr.	3.16	3.13	3.22	3.16	3.18

1. Basic charnockite (basic garnetiferous norite) Neapea Hill, Uganda.
2. Metadolerite. Bunyoro District, Uganda. (Groves, p. 172.)
3. Metadolerite ('mineralogically intermediate between normal dolerite and rocks of thoroughly charnockitic types'). West Nile District, Uganda. (Groves, p. 172, in analytical table named amphibolite).
4. Basic charnockite, Lassabacka, Varberg.
5. Garnetiferous amphibolite, Getterö island, Varberg.

Table VIII (cont.).

	1	2	3	4	5
Niggli values:					
si	96.9	112.8	117.1	102.0	102.5
qz	−17.1	−3.2	−11.7	−25.2	−17.5
al	18.9	19.2	15.1	19.3	17.9
fm	47.2	48.8	51.2	52.6	52.1
c	30.4	28.0	26.5	21.3	25.0
alk	3.5	4.0	7.2	6.8	5.0
k	0.02	0.06	0.47	0.29	0.48
c/fm	0.64	0.57	0.52	0.41	0.48
Norms:					
Q	—	3.66	1.35	—	—
or	0.56	1.11	12.79	8.08	14.64
ab	14.15	14.15	14.15	18.19	5.57
an	34.75	30.86	15.85	25.50	26.92
di	25.04	21.00	28.28	14.43	21.03
hy	5.22	21.56	16.42	13.83	16.03
ol	15.68	—	—	1.71	5.64
il	1.37	6.16	7.77	9.93	4.55
mt	1.86			8.31	4.84
ap	0.34	0.34	0.67	—	—
sal	49.46	49.78	44.24	51.77	47.33
fem	49.51	49.06	53.14	48.01	52.09

1. III : 5 : 4 : 5	(persodic)	or : ab : an	1.13 : 28.61 : 70.26
2. III : 5 : 4 : 5	(persodic)	or : ab : an	2.41 : 30.68 : 66.91
3. III : 5 : 3 : 3	Kentalenose	or : ab : an	29.89 : 33.07 : 37.04
4. III : 5 : 4 (3) : 4	Auvergnose	or : ab : an	15.61 : 35.13 : 49.26
5. III : 5 : 4 : 2	(dopotassic)	or : ab : an	30.93 : 12.19 : 56.88

A similarity in chemical composition seems equally admissible between the most acid types of the charnockitic rocks and the surrounding gneiss from Varberg as between corresponding rocks from Uganda. The specific gravity of the compared felsic charnockite from Varberg is very nearly identical with that of the gneiss (2.66 against 2.63). Of the Niggli values *alk* and *k* are identical, and others show only insignificant divergences, with the exception of *si*, which is higher in the felsic charnockite. This difference is, however, only due to the content of free quartz, as shown by the Niggli *qz* values. The difference in *qz* for the two rocks is 22.3, very closely corresponding to the difference in *si* (20.6). The amount of free quartz in the felsic charnockites is, however, variable. The other analysis of this type, given in Table IV, has an essentially lower content of SiO_2. This is due to the fact that for the two analyses I chose two specimens which, under the microscope, proved to represent types with the largest and the smallest amount of quartz respectively. In silica content more intermediate felsic charnockites are perhaps most plentiful and would then, in this respect, probably in many cases more exactly coincide with the gneiss. The conclusion then suggests itself that many of the felsic charnockites may be heteromorphic equivalents to the orthogneiss in its pluto-metamorphic state.

We may now turn to compare the basic charnockites with chemically more or less equivalent rocks within the surrounding gneiss formation. Just as the surrounding gneiss was analysed with reference to a presumed connection with certain rocks within the charnockitic area, two analyses were made of basic rocks within the gneiss complex for comparative study.

In Table VII are reproduced the two analyses of the basic charnockites from Table I (Nos. 1 and 2). No. 3 is an analysis of a typical representative of the relatively widespread occurrences of metagabbros inland, east of the Varberg area. Analysis No. 4 is that of a normal amphibolite interlayered in the gneiss formation. Analysis No. 5 is representative of the garnetiferous amphibolite from the island of Getterö, close to Varberg, surmised to represent a partial charnockitisation of a primary doleritic dyke.

For further comparison in respect of chemically closely related rocks outside the province, I have reproduced in the same table two analyses (Nos. 6 and 7) of a hyperite from Nyed in Värmland and what MAGNUSSON has defined as a 'hyperite-amphibolite' from the same occurrence.[1] Remarkable similarities are apparent between the analyses and the Niggli values and the norms of the basic charnockites from Varberg and of the hyperite from Nyed, though the rocks are taken at places more than 200 km apart. Disregarding a slight difference in free quartz, one may say that the chemical composition of the two rocks is practically identical. The consequence would be that if, as anticipated, plutonic metamorphism has effected but little change in chemical composition, the primary rock which has given rise to the basic charnockites may well have been a hyperite, or a norite, its more abyssal equivalent. In any case the differences in chemical composition between the basic charnockites and the basic rocks in the surrounding area are not greater than that any of the gabbroic rocks or amphibolites might well have been the primary source of the basic charnockites.

I may again refer to Groves' comparative data of rocks within and without the charnockitic area of Uganda. In Table VIII Groves' analysis of a basic charnockite (basic garnetiferous norite) and of two metadolerites from outside the charnockitic area are reproduced.

Groves comes to the following conclusions: "The 'greenstones' occurring in gneisses removed from the outcrops of the charnockite series become increasingly charnockitic in character as the charnockitic mass is approached". (The name greenstone is from field notes of SIMMON, of the Geological Survey of Uganda. Groves calls them metadolerites in the continuation of his paper). Analysis No. 3 in Table VIII is said to represent "a type mineralogically intermediate between normal dolerite and rocks of thoroughly charnockitic type" (No. 2 in Table VIII). Groves comments thereon that "the differences in chemical composition are slight and concern only alumina and potassium.[2] The analyses show that, if the rocks were originally dolerites — and the evidence appears to warrant this supposition — plutonic metamorphism has effected comparatively little change in the chemical composition. The changes have been chiefly mineralogical" (Groves, p. 173.).

Groves' observations that the outlying dolerites become increasingly charnockitic as the charnockitic area is approached has far-reaching significance in respect of the origin of the charnockites in general. Similar indications within the Varberg district can be observed regarding the garnetiferous amphibolites of Getterö and Lassabacka, in the latter locality in direct connection with typical basic charnockites. Microscopical study has already indicated a partial charnockitisation of these rocks, and in many respects the analysis of the rock from Getterö shows the same affinities to the basic charnockites of the Varberg area as Groves' corresponding analyses of his basic charnockite and a dolerite "mineralogically intermediate between normal dolerite and rocks of thoroughly charnockitic type" from Uganda (Groves, p. 173).

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[1] Sveriges Geolog. Undersökning, Ser. Aa, No. 114, 1929, p. 26.

[2] Groves has written 'soda' but has corrected it to 'potassium' (personal communication).

In Table VIII are also reproduced the analyses of the basic charnockite from Lassabacka and of the Getterö amphibolite, together with Groves' analyses, for the sake of comparison. With respect to the Varberg rocks the essential difference in chemical composition refers to the relative amount of Na_2O and K_2O. An interesting coincidence is that the same variation occurs as between the Uganda rocks. The Niggli value k for the rocks, both from Uganda and Varberg, which have been presumed to represent a partial charnockitisation (Table VIII, Nos. 3 and 5) are 0.47 and 0.48 respectively, whereas the adjacent basic charnockites have k-values 0.02 and 0.29. In this case the difference is less between the Varberg rocks than between the Uganda rocks.

In other respects too the analyses of the basic charnockites of the Varberg district and of the basic rocks within the surrounding gneiss complex show chemical affinities corresponding to those found in Uganda, indicating a corresponding genetical relationship.

To visualize the chemical distribution of the charnockitic rocks of the Varberg area, as compared with the charnockites from other regions and continents, a selected number of 44 analyses of typical charnockites, and with them presumably cometamorphic rocks, as well as of the 9 available analyses of rocks from surrounding formations, have been plotted in a diagram and 5 graphs. The numbers of the analyses, now consecutive, are given below. The 9 analyses of adjacent non-charnockitic rocks are indicated by italic numbers in the list below and by open rings in the diagram and graphs.

1. Varberg, basic charnockite, Lassabacka
2. » » » Träslövsläge
3. » gabbro-diorite, outlying rock
4. » amphibolite, » »
5. » garnetiferous amphibolite, Getterö
6. Nyed, hyperite
7. » hyperite-amphibolite
8. Varberg, intermediate charnockite, Apelviken
9. » » » Fästningsberget
10. » » » (leucocratic subspecies), Träslövsläge
11. » » » (abnormal subspecies), Björka-Trönninge
12. » sub-acid charnockite, Traneberg, Varberg town
13. » felsic charnockite, Träslövsläge
14. » » » Himle
15. » hybrid rock, Träslövsläge
16. » aplite granite, Träslövsläge
17. » orthogneiss of surrounding formation
18. Arendal, basic charnockite (basic arendalite)
19. » intermediate charnockite (intermediate arendalite)
20. » sub-acid » (sub-acid »)
21. » acid » (acid »)

22. Madras, basic charnockite
23. » intermediate charnockite
24. » » »
25. » acid »
26. » » »
27. » » »
28. Mysore, basic charnockite
29. » » »
30. » intermediate charnockite
31. » » »
32. » acid charnockite
33. » aplite granite
34. Ceylon, basic charnockite
35. » intermediate charnockite
36. » » »
37. » » »
38. » » »
39. » sub-acid charnockite
40. » » »
41. » acid charnockite
42. Uganda, basic charnockite
43. » metadolerite
44. » »
45. » intermediate charnockite
46. » acid charnockite
47. » orthogneiss of surrounding formation
48. Ivory Coast, basic charnockite
49. » intermediate charnockite
50. » acid charnockite
51. Enderby Land, acid charnockite
52. » ‘enderbite’
53. » granulite

As the classification of the charnockitic rocks has to an essential degree been based on variations in the content of alkalies, an Or-Ab-An triangular diagram is chosen as being most illustrative (Fig. 29.). As can be seen, the reproduced 38 analyses of typical charnockites, as well as 6 analyses of rocks closely associated with them in the field (Nos. 13—16, 33, 53) and 9 analyses of adjacent rock formations (Nos. 3, 4, 5, 6, 7, 17, 43, 44, 47) are, with few exceptions, fairly uniformly distributed within a wide zone across the diagram.

With two exceptions, all the basic charnockites lie within the line Or 12. These include Nos. 1 (Varberg), 18 (Arendal), 22 (Madras), 28 and 29 (Mysore), 42 (Uganda) and 48 (Ivory Coast). The exceptions are No. 2 from Lassabacka (Varberg), found in association with the highly potassic garnetiferous amphibolite referred to above. The higher content of potassium in this basic charnockite (or : ab : an 15.61 : 35.13 : 49.26) may therefore be explained by the circumstance that a sodaic influx in connection with the metamorphic conversion, has not fully compensated the primary high content of potassium in the adjacent rock.

The other exception is the basic charnockite from Ceylon (No. 34). Adams has

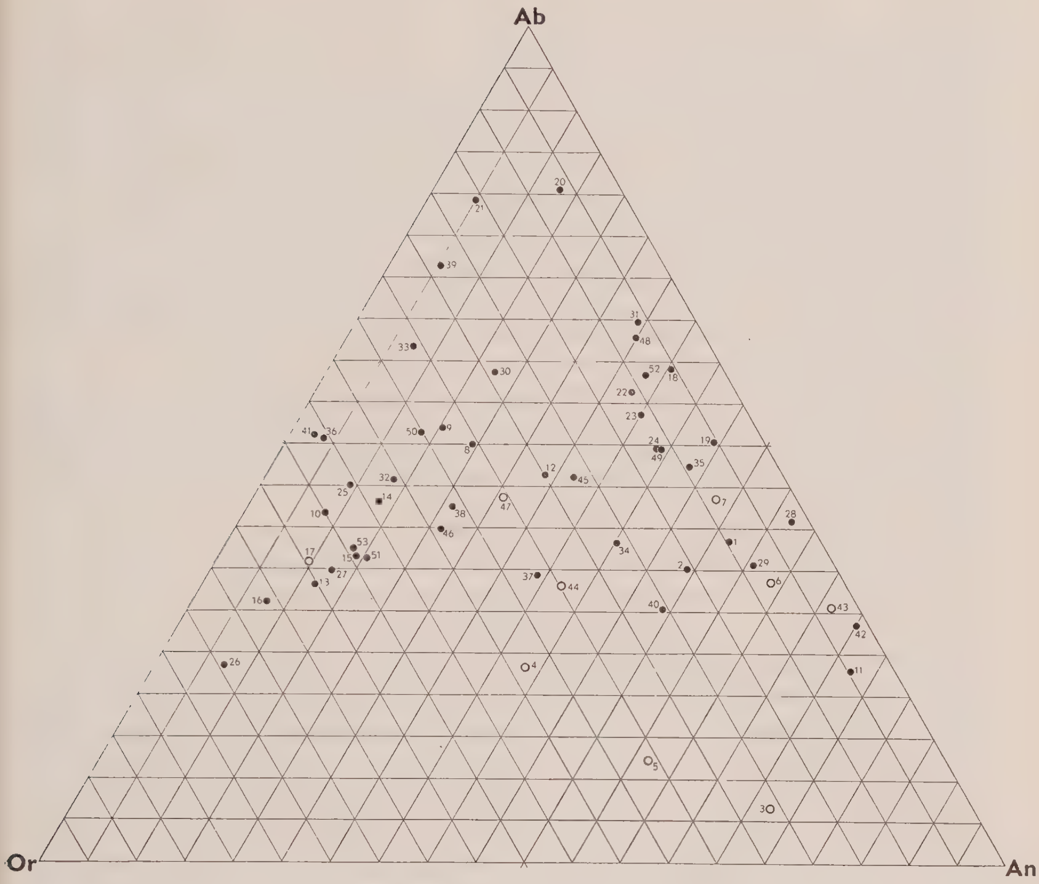

Fig. 29. Or—Ab—An-diagram.

already indicated its exceptional composition by naming it 'garnetiferous orthoclase norite' (or : ab : an 21.43 : 38.30 : 40.27). It has been included as representing the sole analysed specimen from Ceylon pertaining to the basic charnockites.

The analyses of the basic rocks outside the charnockitic area in Varberg and Uganda have been included in the diagram for comparative study. The variations in the proportions or : ab : an in these rocks (Nos. 3, 4, 5, 43 and 44) disperses them over a wider area. A close chemical relationship in other respects is obvious in graphs 1—3.

Of the intermediate charnockites from Varberg, Nos. 8 and 9, representing the normal rocks of this group, are found to lie very centrally in the diagram, indicating a monzonitic composition with about 'ab' 50, 'or' 30 and 'an' 20. The sub-acid charnockite (No. 12) has much the same position. The leucocratic species (No. 10), with only 8.37% 'an' (or : ab : an 49.91 : 41.72 : 8.37), gives this rock an extreme position towards the Or-Ab margin.

Analysis No. 11 represents the species referred to above as a wholly deviating type. The fine-grained to aphanitic rocks of this category have been classed with the intermediate group solely on account of the content of silica and the amount of free quartz. The Niggli values are *si* 135.8, *qz* +15.0. In other respects, however, the analysis of the rock reveals similarities to the basic charnockites. The extremely high content of an 72.23 (or : ab : an 4.70 : 23.07 : 72.23) is however extraneous also for the basic charnockites. As already indicated above (p. 259) one may reasonably explain the abnormal composition of these fine-grained rocks as appertaining to basic charnockites which have subsequently been silicified by a later influx. The sporadic occurrence of scapolite in some of these rocks points in the same direction. Furthermore, the contents of minor constituents, as determined by Dr. Landergren, points to the same conclusion. This is especially the case with the content of V and Ni, which is high in the basic charnockites and also in the rock No. 11 from Björka (see appendix II). Its quartzite-like appearance may also be connected with such a secondary silicification.

Intermediate charnockites from other regions present some further points of interest. Beginning with the Arendal rocks from Norway we find that the sub-acid charnockite No. 20 occupies an abnormal position on account of its extreme content of Na_2O (or: ab: an 6.46: 80.49: 13.05). The only other analyses which approach the position of No. 20 is a sodaic sub-acid charnockite from Ceylon (No. 39) with or: ab: an 23.19: 71.26: 5.55.

The remainder of the intermediate charnockites are spread over a wide field in the diagram, with no tendency to concentration even for rocks from the same region. In this group we can reckon most of the analysed rocks from Ceylon, to which Adams has given the general name 'charnockite' in Holland's sense. However, all analyses of charnockites (acid charnockites as here named) from Holland's type localities have over 75% SiO_2[1] whereas only one of Adams' analyses (No. 41) shows a SiO_2 content exceeding 75%. All the rest of the analyses which have been included in the list above have a silica content between 65.89 and 71.74%. Adams also indicates that "the varieties selected for analyses, as typical for the series as developed in Ceylon····generally contain about 10% less silica than the charnockite from the type locality near St. Thomas Mt." (Adams, p. 448). According to the classification employed in this paper, Nos. 35—38 in the list of analyses from Ceylon would be reckoned as intermediate charnockites, Nos. 39—40 as sub-acid charnockites and only No. 41 as an acid charnockite (charnockite sensu stricto of Holland).

In the diagram the six analyses Nos. 35—40 from Ceylon are spread over a wide area in consequence of their very varying content of K_2O and CaO. The or : ab : an proportions vary from 9.44 : 47.43 : 43.13 to 45.51 : 50.78 : 3.71. One of the analyses (No. 37) is of interest in respect of its position very near the numerical centre of the diagram with approximately equal values for 'or', 'ab' and 'an' (or : ab : an 31.69 : 34.28 : 34.03).

The wide distribution of the intermediate charnockites in the diagram has a certain significance as in every way contrasting with Holland's assumption that "the apparent consistency in composition" of the intermediate charnockites favoured

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[1] The distinguishing content of SiO_2 for the different divisions of the charnockite series given by Holland, are:

acid charnockites (Holland's charnockites sensu stricto)	about	75 %
intermediate charnockites (Holland's intermediate division)	»	64 %
basic charnockites (Holland's basic division)	»	50—52 %

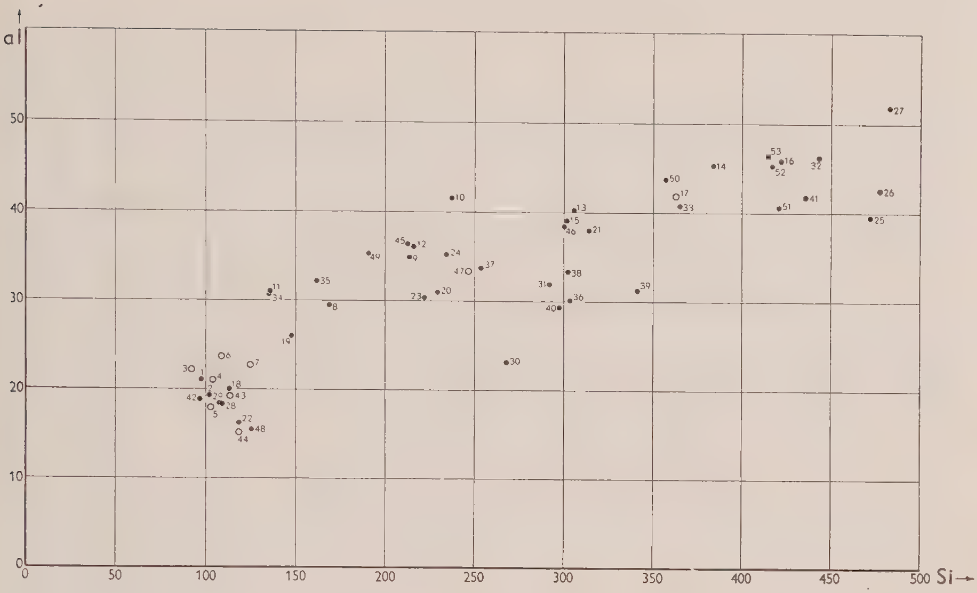
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Fig. 30.

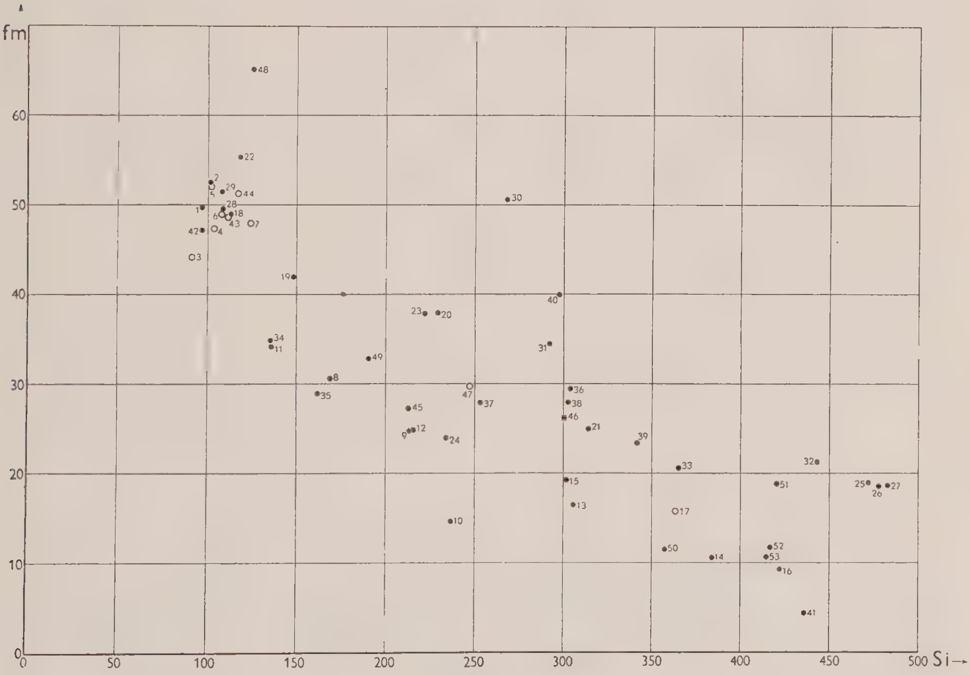
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Fig. 31.

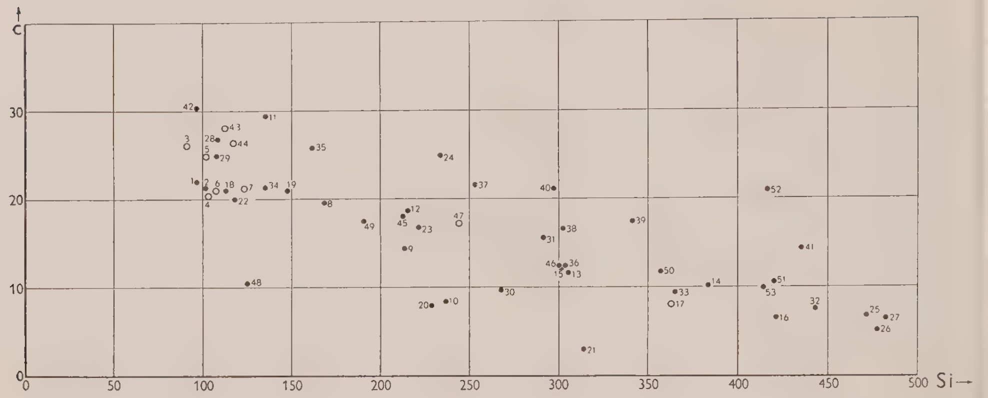

Fig. 32.

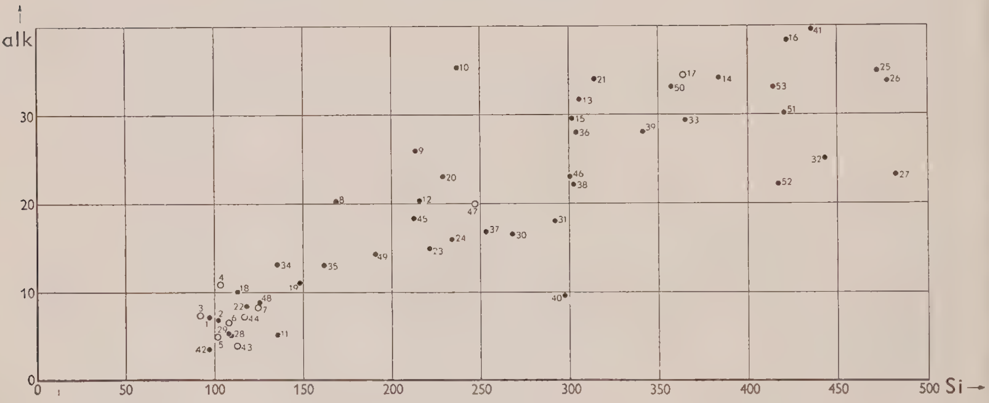

Fig. 33.

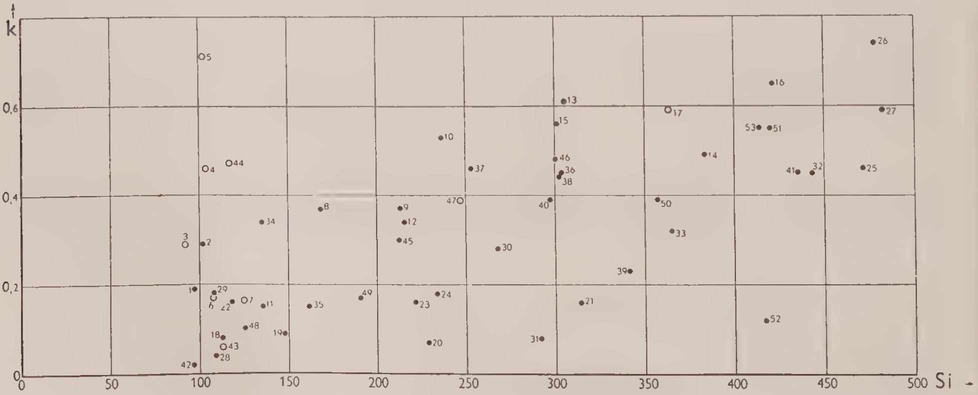

Fig. 34.

the suggestion to regard them "as the result of the direct consolidation of the original magma" (Holland, p. 149).

The acid charnockites are also widespread in the diagram, though with a tendency to concentration within a section with Ab between 40 and 50 %. The acid charnockite from Arendal (No. 21), with the exceptionally high content of Na_2O (or : ab : an 15.79 : 79.06 : 5.05) is the only marked exception. As no true acid charnockites are represented within the Varberg area, the felsic charnockites, probably corresponding to many so-called granulites from other charnockitic regions, are found in the diagram located within the boundary of the acid charnockites, along with the 'granulite' of Tilley from Enderby Land (No. 51).

In the graphs (Fig. 30—34) the silica content is naturally the primary dividing point. The most acid of the analyses reproduced are seen to be those of the three charnockites from Madras (Nos. 25, 26 and 27), with an *si*-content of about 480. The next group is represented by the acid charnockites from Mysore (No. 32) and Ceylon (No. 41), with *si* about 440. A following group is characteristically comprised of the Enderby Land rocks (Nos. 51, 52 and 53) with *si* round about 420. As regards the basic and intermediate charnockites, there is little to add beyond what has already been advanced. In the graphs the basic charnockites are well assembled within a very limited area; the intermediate charnockites are, as in the Or-Ab-An diagram, spread over a wide field.

The graphs have been planned so as to give an approximate idea of the variability of the charnockite rocks in respect of different chemical aspects. No attempt has, however, been made to indicate connections between different regions as no conclusive evidence in this respect is to be found. This would accord with an assumed origin of the charnockites as being regenerated rocks from older formations. The basic charnockites from all regions, however, seem to be chemically related, indicating their universal source from basic igneous rocks of gabbroic composition. The acid charnockites and related rocks would then vary in accordance with the general composition of the prevailing acid rocks of the surrounding area. The intermediate charnockites seem in most cases to have no chemically equivalent rocks within the adjacent formations and have therefore of late in many instances — and now also in the Varberg area — been interpreted as rocks of a hybrid nature. When more data as to the chemical composition of rocks outside a charnockite area become available, more definite conclusions as to their co-metamorphic affinity to adjacent charnockitic rocks may perhaps be drawn. An indication may be found in the circumstance that the ultra-basic charnockites —representing Holland's ultrabasic division —seem mostly to occur in regions where mono-mineralic rocks, in the form of dunites, serpentines etc., are to be found or can be anticipated in the surrounding rock formations. In the Varberg region no rocks of ultra-basic composition are found in the surrounding complex, and no ultra-basic charnockites occur within the charnockite area.

Earlier postulations concerning the origin of the charnockitic rocks

In the preceding chapters I have in different connections hinted, en passant, at some conclusions relating to the origin of the charnockitic series of the Varberg area. Before I take up a further discussion of this question, it may be of interest to present in advance the opinions of different authors, who, either from a theoretical point of view or on the basis of field work, in recent years have more or less definitely stated conclusions regarding the genetical position of the charnockite series. To aid impartial judgment, the principal passages will be quoted verbatim.

To begin with, the opinions arrived at by some authors from a more theoretical point of view may be cited. After the publication of Holland's paper on the charnockite series of Madras in 1900, Rosenbusch was probably the first to try systematically to classify the rocks of the charnockite series. He grouped them together with the anorthosite rocks of Canada and the Adirondacks and with the labradorite rocks of the Ekersund-Soggendal and Bergen rock groups as a "Charnockit-Anorthositreihe" (Elemente 1910, p. 183).

In his textbook The Principles of Petrology Tyrrell says: "The peculiar characters of the charnockite series may be explained in two ways: they are either of primary igneous crystallisation under conditions of high temperature and great uniform pressure or they represent plutonic igneous rocks of the usual characters which have undergone slow recrystallisation in the solid state on being subjected to conditions of plutonic metamorphism" (Tyrrell, 1948, p. 317). Tyrrell defines plutonic metamorphism as follows: "By plutonic metamorphism is meant the changes which are produced in rocks by great heat and uniform pressure" and notes as a most characteristic feature: "As the influence of directed pressure is at most feeble in this type of metamorphism, orientated parallel structures are in general unimportant and give place to even-grained, granulose, directionless structures. Radical recrystallisation without marked directional tendencies thus occurs under conditions of plutonic metamorphism. · · · · The formation of antistress minerals of small specific volume and high density will obviously be favoured by these conditions. · · · · Certain pyroxenitic igneous rocks, as for example the charnockite series, are believed to have acquired their distinctive characters under conditions of plutonic metamorphism" (Tyrrell, 1948, p. 313).

Though not limiting himself to the charnockite problem, J. A. Dunn, in his paper "Granite and magmation and metamorphism" expresses views which, even if they refer to wider fields of Peninsular India, may from a theoretical point of view be applicable in essential details to the origin and metamorphic evolution of the charnockite series, as indicated by Dunn himself.

Dunn states his views as follows: "In India and other countries the oldest archaean schists, of leptynite type, are rather acid in composition, sediments and tuffs, presumably derived from the differentiated granitic shell which formed the primordial sial or crust covering the basic sima. A certain amount of basaltic magma was injected into this acid crust, with perhaps some extrusion of flows, but over wide areas the bulk composition of the crust was essentially acidic.

"The early sediments etc., where deep-folded, would come under the influence of high temperature. In this environment, chemically combined water in the sediments would be in increasingly unstable combination, and would migrate from the deepest zone, possibly taking with it certain other constituents. In this way would arise the 'dry' metamorphic rocks such as the khondolites. Should the heat generated in these dry rocks be sufficient to fuse them, a dry magma would result. The evidence available is not opposed to the view that the hypersthene gneisses, the charnockites, are the products of partial or complete palingenesis of very deep-seated rocks which had lost their water content. In India, the charnockites are associated with dry metamorphic rocks of sedimentary origin, the khondolites, in a region in which constant uplift has permitted their ultimate exposure at the surface. But once this dry magma commences to stope its way upwards, some of its water content may be recovered by assimilation of schists and sediments." (Dunn, p. 231).

The ideas here expressed might explain many points which have been emphasized as evidence of a magmatic origin of the charnockite series of rocks. We could conceive a regenerated charnockitic 'magma' leaving the country rocks, igneous, sedimentary or metamorphic, from which it originated through a palingenetic phase of deep-seated plutonic metamorphism, and thereby gaining a new-born magmatic character with all the intrusive manifestations which Holland has accepted as evidence of an igneous origin.

On the other hand, charnockitic rocks may occur where charnockitic solutions may occasion only a partial rheomorphism, soaking schists along the cleavage-planes, resulting in bands or layers of charnockitic rocks in every respect suggestive of a purely metasomatic origin. The partial charnockitisation of such a rock complex must then have taken place in situ, whereas apparently fully intrusive charnockites in the immediate environment would represent such parts of the rock complex as have succumbed to a complete palingenesis and then in a remobilised state left their mother-rock and reached higher zones, where a partial metasomatic charnockitisation may already have taken place.

Jens Bugge discusses in detail the "diffusion in the solid state as a rock-building process" as an essential agent in the formation of the charnockitic rocks of the Arendal district. Especially the nature of the felspars is taken to prove the formation in situ of the rocks, owing to an ionic penetration along or into the crystal lattice (J. Bugge, 1946, p. 32).

B. Jagitsch later took up the question of diffusion in the solid state in respect of rock transformations and passed on to a critical discussion of Bugge's opinion on this subject. I must refer to Jagitsch's paper for his running commentary and here restrict myself to his concluding remark: "Dass die von Bugge angeschriebenen und oben teilweise referierten Reaktionsgleichungen daher nur die Bedeutung eines Diskussionsvorschlages haben, soll hier besonders understrichen werden" (Jagitsch, 1949, p. 68–84). In connection with an investigation of a charnockitic area in the pre-cambrian of western Greenland Ramberg says: "On field evidence and experimental evidences as well as on theoretical grounds the writer considers it unlikely that large-scale diffusion through solid rocks preferably takes place through the silicate lattices" (Ramberg, p. 52).

It is not my intention to enter into a discussion as to whether diffusion in the solid state might have co-operated in the metamorphic transformation of charnockitic rocks. The whole question of reactions in the solid state in respect of the dry charnockitic rocks must evidently for the present be regarded as a purely theoretical proposition. I deem it most advisable to concur in Eskola's opinion, when he says: "Gegenwärtig können wir noch sehr wenig bestimmtes darüber sagen, welche Bedeutung den reinen Kristallgitterreaktionen bei der Gesteinsmetamorphose zukommt" (Eskola in Barth-Correns-Eskola, p. 328)[1]. In any case no direct indications have been observed suggesting that reactions took place owing to interlattice large-scale diffusion within the Varberg charnockitic area. As against the term 'interlattice diffusion' I have used 'intergranular diffusion' in connection with a presumed large-scale hybridisation.

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[1] See also Bowen, 1948, p. 85 where he writes: "in the present state of knowledge it seems doubtful that it (solid diffusion) can be regarded as a factor of major importance in geology."

After referring to these more theoretical considerations, I may proceed to the results gained from direct field work in respect of the origin and petrogenetical position of the charnockite rocks, provided that they conform to Holland's definition of the charnockite series.

Holland's view of the igneous origin of the charnockites of Madras is well known. It may suffice to quote a single sentence, representing his perhaps chief line of argument on this question. He writes: "The most straightforward inference to be drawn is, it seems to me, that the charnockite attained its present position *after* the crushing of the gneiss, that, in fact, it has trespassed across the foliation planes of the latter. This implies that the charnockite has behaved after the fashion of an igneous rock, and that it is younger than this particular biotite-gneiss near Salem" (Holland, p. 226). But Holland does not overlook that the charnockites present features of exceptional character for igneous rocks. He says: "No evidence, moreover, has been discovered which is definitely inconsistent with our conclusions as to the origin of these rocks, though there are some features which are sufficiently unusual in normal igneous rock to demand a special explanation" (Holland, p. 244). Of the different types of charnockitic rocks described by Holland, he says "by far the most prevalent type has an intermediate silica percentage and the occurrences of anything approaching large masses of acid or basic types are comparatively rare" (Holland, p. 249). These rocks of intermediate chemical composition represent the intermediate division of Holland's charnockite series. It is of interest to note that Holland himself discusses the possibility that these rocks may be of a hybrid nature. He writes: "A mixture of equal parts of norite and (acid) charnockite would have a silica percentage of 64. It does not necessarily follow, however, that these intermediate varieties of the charnockite series are actually the result of the mixing together of previously differentiated charnockite and norite magmas". Against the suggestion of such a syntectic origin Holland states it as his own opinion: "until, therefore, further observations show that the apparent constancy in the composition of these intermediate varieties is only the result of the limited number of determinations which I have been able to make, I prefer to claim this point as evidence in favour of regarding the intermediate varieties as the result of the direct consolidation of the original magma, whilst the acid and the basic masses are the result of more perfect differentiation, favoured by purely local conditions" (Holland, p. 149—50).

Holland's "limited number of determinations" exemplifying the "apparent constancy in the composition of the intermediate varieties" has now been augmented by manifold analyses of typical charnockite rocks from both India and other regions. These new analyses suggest directly opposite conclusions — i.e., that the intermediate charnockites are characterised by an inconsistency in their chemical composition.

We may now turn to further work within the charnockite area of India, subsequent to Holland's classical paper. The literature is, however, very extensive. In his paper on the charnockite rocks of Mysore (1945) Rama Rao quotes over 30 references published after 1910 dealing with the Indian charnockitic rocks and problems connected with them. Reference can only be made here to some of the principal papers in which the origin of the charnockite rocks has been dealt with.

I may begin with Holland's successor as director of the Geological Survey of India, Sir L. L. Fermor.

In 1936 Fermor wrote: "The most important general subdivision of the Peninsula is into two, which may be termed regions, dependent on the absence or presence of the charnockitic series", and continues: "Although chemically considered, there is a compositional parallelism between the two regions, yet metamorphically considered there is a general difference, in that the charnockitic region has been carried to a higher general grade of metamorphism, so that on the whole the rocks are everywhere in a hypo-metamorphic condition. The evidence adduced by Sir Thomas Holland in favour of treating the charnockite series as originally of igneous intrusive origin seems conclusive, but it is impossible to ignore the views of VREDENBURG and STILLWELL that in its present condition the series must be regarded as composed of highly metamorphosed rocks. In fact the rocks of the charnockite series appear to be in a hypometamorphic condition and must either have consolidated originally at considerable depths or have been subsequently so buried." (Fermor, 1936, p. 42—46).

A few pages further on (p. 48) Fermor continues "from a consideration of the orographical map of India we see that the charnockitic region is on the whole more elevated than the non-charnockitic region, although composed of rocks that must have been once at greater depth below the surface. This means that there must have been a rise of several thousand feet of the rocks of the charnockitic region relative to the rocks of the non-charnockitic region. Further, this relative uplift must have taken place after the isogeotherms in the earth's crust had fallen sufficiently in the charnockitic region, prior to the fall of pressure, to permit the rocks thereof, when raised to levels of smaller pressure, still to preserve their hypo-morphic impress in toto or in part. Further, this relative uplift must have taken place without the general application of stress · · · ·".

Although in this paper he accepts on the whole Holland's view as to magmatic origin of the charnockite rocks, Fermor's conclusion that the charnockitic region must once have been buried to great depths below the surface indicates that he reckons with considerable metamorphic influence.

Twelve years later, in an obituary notice on Thomas Holland, Fermor expressed a more personal opinion. He wrote as follows: "Although it seems likely that the hypersthene character of these South Indian rocks will prove ultimately not to be due to a common magmatic origin, but to be a signature-tune of common high grade metamorphism effected at unusual depths below the surface, yet to Holland will always belong the credit of having brought vividly to the notice of petrographers this peculiar set of rocks, and of having directed attention to the close study of a part of India that exhibits a generally higher grade of metamorphism than the remainder of the Peninsula".

In 1918 E. W. VREDENBURG published an interesting paper on "Considerations regarding a possible relationship between the Charnockites and the Dhawars". Although he concludes his paper with the words "we are only on the threshold of the study of these interesting rocks", Vredenburg had, as a result of his field investigations, come to conclusions of general interest on the subject of the origin of the charnockitic rocks. Referring to Mysore he says, "the Dhawars and the charnockite series are mutually exclusive; where the one stops, the other commences and vice versa. Although the outcrops of both series approach quite close to one another, the passage from the one to the other is quite irrevocable. Truly typical Dhawars have nowhere been observed, in Mysore, in typical charnockite area, while not a single outcrop of charnockite has been described in the Dhawar area. Where the two great masses come nearest to one another, small patches, in the published surveys, have been ascribed to one or to the other in such a manner as to convey the impression that the surveyors experienced some perplexity in deciding to which of the two series they should ascribe some of the smaller outliers" (Vredenburg, p. 437). And later on the same page: "a careful examination of the admirable geological map published by the Mysore Geological Department forcibly conveys the impression that the charnockites and the Dhawars may be vicarious, that the charnockite series may be a facies of the Dhawar series. Both series give rise to just the same type of topography, the Dhawar outcrops, whenever sufficiently massive, forming hills similar in appearance to those formed by massive outcrops of charnockite". By Indian gelogists the Dhawar series is universally assumed to be composed of an igneous series and a sedimentary series. Vredenburg now comes to the conclusion that the charnockite series is an intensely metamorphosed facies of the igneous series of the Dhawars. He says: "In the Dhawar area, adjacent to the charnockite area of Southern India, the Dhawar series is represented almost solely by its igneous members; consequently most of the rocks, representing its intensely metamorphosed facies in the charnockite series, are also igneous. In the north-eastern portion of the Peninsula, the Dhawars consist of alternations of igneous and sedimentary strata; their intensely metamorphosed representatives in that same part of the Peninsula consist of alternations of igneous charnockites and sedimentary khondolites" (p. 444). "It seems thus, from independent evidence, that the charnockites may be regarded as intensely metamorphosed representatives of the igneous members of the Dhawars, the khondalites as intensely metamorphosed representatives of their sedimentary members" (p. 442). Without entering upon any discussion as to the nature of the metamorphic development, Vredenburg had in any case definitely departed from Holland's interpretation of the charnockite origin as being purely magmatic.

B. Rama Rao has published a series of papers relating to the charnockite series in the province of Mysore. As during continued field work he subsequently modified his conception as to the origin of the rocks in question, I may confine myself to quoting the opinion he expresses in his most recent paper (Rama Rao 1945). In a concluding chapter (p. 162) Rama Rao says: "it would not be the plutonic metamorphism of normal igneous rocks which have given rise to the present-day charnockites, but it would be the plutonic metamorphism of composite series of rock formations both igneous and sedimentary, of divers ages · · · · Consequently, I would regard the charnockites not as belonging to a petrographic province as originally interpreted — namely the differentiated phases of crystallisation of a normal plutonic intrusive magma (Holland) — but as of a metamorphic province wherein the combined effects of a repeated series of alterations under different periods of metamorphism of a composite series of rock formations of different ages, have given rise to a series of hypersthene granulites of very variable composition". In contrast to Holland's statement from the Madras area Rama Rao observes that "there are not large independent bodies of intermediate charnockites in Mysore · · · ·" (p. 155). Referring to Vredenburg's conception of the origin of the charnockites in Mysore, he writes: "Arriving at this conclusion that the charnockites are undoubtedly metamorphic in origin and have been reconstructed from several pre-existing rock formations, we might just as well consider here how far we can support Vredenburg's ingenious inference that the charnockites represent the intensely metamorphosed facies of the volcanic series in the Dhawars. The mere fact of absence of the charnockite rocks in the north-western parts of Mysore where large bodies of the Dhawar schists are in direct contact with the intrusive granites – one of the reasons adduced by Sampat Iyengar to controvert Vredenburg's views — need not by itself form any bar for the consideration of Vredenburg's inferences. As I have stated elsewhere (Rama Rao 1936, p. 220), Mysore shows progressive metamorphism from its north and northwest to south and southeast, and the southern and south-eastern portions of Mysore attain the highest stage or grade of metamorphism observable in the State. Since the charnockites are found only in regions of intense alterations, subjected to repeated metamorphism we cannot and should not expect to find charnockite rocks — if originated under such intense alterations as shown in this paper — to occur in the northern parts of Mysore. · · · · Petrographic evidences no doubt favour to a certain extent Vredenburg's inferences and would show that not merely the basic flows but even their associated impure sediments may be reconstructed into the charnockite types, but field evidences, by actual tracing of the undoubted Dhawar belts of schists — by progressive gradation — into the typical charnockite members, remain yet to be produced. Consequently, his inferences will have to continue for the present — till definitely proved one way or the other — as probabilities worthy of further investigations" (Rama Rao, 1945, p. 156—158).

In his interesting paper on "the charnockite series of Bastar State and Western Jeypore" P. K. Ghosh gives a detailed microscopical description of the charnockite rocks and of the reactions in their mineral association. He indicates his conception as to the origin both in an introductory and in a concluding remark. In the introduction to his paper he says: "the differentiation effect observed in this suite of rocks (the charnockite series of the area described) is not of magmatic character, but is one connected with metamorphism and hybridism". And as a concluding remark he adds: "From considerations set forth above it is clear that the basic and the ultrabasic portions of the series are due to heat and pressure metamorphism, but the intermediate and the acid rocks owe their origin to a process of assimilation" (Ghosh, p. 53).

I have quoted somewhat extensively the conceptions of recent workers on the Indian charnockite regions in order to indicate the trend towards ascribing to the charnockitic rocks a complex metamorphic evolution from more or less heterogeneous rock formations. I cannot here deal with the detailed observations on which their opinions are founded. For those I must refer the reader to the literature. But we can at any rate conclude that later research within the charnockite area of the Indian Peninsula has led to the important conception that in all probability rocks of the charnockite series are not of normal magmatic origin but are the result of a deep-seated metamorphism of rocks which may have been of heterogeneous origin.

Opinions differing in some respects have, however, been advanced. As recently as 1948 K. P. Rode, for instance, writes as follows: "the formation of hypersthene and other associated minerals within acid rocks, which constitutes the most characteristic attribute of the charnockites, appears to be restricted to the oldest cycles of orogenesis in the archaean period and has apparently much to do with high grade metamorphism of plutonic depths" (Rode, p. 288). Thus far Rode's view conforms with those of the Indian authors quoted above. But when he says: "The basic intrusives — (basic charnockites) — are post-khondalitic in age, whereas the acidic charnockites form part of the basement complex of much earlier age" his line of thought is divergent. It seems hardly probable that the specific metamorphism, which we must assume to account for the sparse occurrence of the charnockitic rocks, can recur within the same area at different epochs. And when Rode brings in gravitative crystallisation as a leading feature in order to explain the different types of the basic charnockitic rocks, he has to postulate the occurrence of considerable masses of hornblenditic rocks, "with felspars as a very minor and occasional constituent". Large masses of such rocks are not, however, found in many areas of charnockite rocks where basic charnockites, on the other hand, are of usual occurrence. Rode's attempt at a theoretical explanation can therefore hardly be said to tally with known field observations in many charnockitic regions.

We may now leave the Indian Peninsula and the theories advanced in respect of the origin of the charnockites within that region.

Geographically the charnockite province of Ceylon is naturally to be considered as a more or less direct continuation of the Indian area. In his paper "The Geology of Ceylon", ADAMS says: "In Ceylon a series of rocks which evidently represent a southward continuation of this charnockite series of southern India occupies large areas in the south central portion of the Island".

Adams does not discuss the petrogenetic problems of the Ceylon charnockites in any detail, but from the wording in his descriptions, in which he repeatedly speaks of intrusions of the charnockite rocks ("a detailed petrographical study has been made of the charnockite of this intrusion", quoted as an example from p. 450), it is evident that he accepts Holland's view as to an igneous origin.

The charnockite regions of Equatorial Africa seem to afford typical representatives of the different species of the charnockite series. The principal localities are found in Uganda and on the Ivory Coast, both the subjects of recent and detailed descriptions.

In his interesting study of the charnockite series of Uganda, GROVES begins by emphasizing that the "striking parallelism between Holland's series in India and Uganda justifies reference to the latter as the Uganda charnockite series". I cannot in this connection dwell on the very essential part of Groves' paper dealing with the conversion of the mineral composition due to metamorphic processes. References thereto have been made under earlier headings. Here I will restrict myself to considering his view on the origin of the rocks in question.

Groves attributes the development of the Uganda charnockite series to plutonic metamorphism in Tyrrell's sense. As an example may be quoted his observations regarding the petrogenesis of the Mt Wati area: "· · · it is apparent that the trend of changes is not that of contact metamorphism but of plutonic metamorphism. Not only is this true of the orthogneisses forming the great body of the rocks, but also of the greenstones (in continuation named metadolerites) and felsites instrusive in them". Groves analysed the surrounding rocks and found that "the analysed specimen of gneiss from just outside the charnockite area compares so closely with the charnockitic specimen from two miles away that the two rocks appear to be both co-magmatic and heteromorphic". The gneiss is said to coincide "perfectly with the variation diagram, showing in the clearest manner that it is consanguineous, not only with the nearest charnockitic rock, but with the charnockite series of a belt of country nearly 100 miles long. This analysis affords strong confirmation of the view that the charnockite series of Uganda originated in the plutonic metamorphism of a normal series of calcalkali plutonic rocks together with their associated doleritic rocks."(Groves, p. 193, 195, 197).

Among facts given by Groves in favour of the formation of the charnockite series by plutonic metamorphism in Uganda, I may quote those referring to the petrogenetical side of the problem:

a. "all known areas of the charnockite series in the world are in regions where long-continued deep denudation has exposed the most ancient rocks of the continents.

.... In general, the denudation has cut down deeper in the northern half of the Protectorate than in the southern, and it is to this northern part that the exposures of the charnockite series are confined. It would appear, then, that the charnockite series occurs only in those parts of the world which have at one time been in zones of plutonic metamorphism".

b. "the geological setting among orthogneisses and paragneisses".

c. "grading of orthogneisses, by increasing stages of plutonic metamorphism into their charnockitic equivalents".

d. "occurrence of metadolerites, passing by successive stages of plutonic metamorphism into their charnockitic equivalents".

e. "the abnormal petrographical and mineralogical features, which are so in spite of the fact that the Uganda suite consists of chemically normal members of the calc-alkali series."

f. "uniformity of the mineral species and the marked presence of dry minerals throughout the series".

The remainder of Groves' facts in favour of the formation of the charnockite series by plutonic metamorphism are of equal importance but refer to purely mineralogical details. Summing up the facts now quoted, it may be said that they seem to afford rather convincing support for the opinion that the rocks belonging to the charnockitic series of Uganda were formed by plutonic metamorphism of the surrounding rocks. The generalised conclusion of Groves' conception would be that the chemical composition of any series of charnockitic rocks is dependent on the chemical composition of the surrounding rock area and consequently that the charnockite series of rocks is not characterised by any specific chemical composition. In different areas the chemical composition would then be dependent on the composition of the different rocks building up the old land surface, igneous, sedimentary or both combined.

It may be of interest to note that G. M. Stockley has identified charnockitic rocks in the Njombe district in Tanganyika Territory (Stockley, p. 16.). He does not, however, enter into any discussion as to their petrological position or genesis.

Though to a certain extent expressed in different words, we may say that Groves' view as to the charnockitic rocks of Uganda tallies in all principal details with the results at which Vredenburg, Ghosh and Rama Rao have arrived as a result of their recent studies of the Indian occurrences.

I shall now turn to the West African charnockite areas. Lacroix was the first to mention the occurrence of charnockitic rocks on the Ivory Coast. In 1910 he published a short paper "sur l'existence à la Côte d'Ivoire d'une série pétrographique comparable à celle de la charnockite". Four analyses indicate the presence of acid, intermediate and basic types (Lacroix, p. 21). As Lacroix does not enter into any discussion relating to the origin of the rocks, it may suffice in this connection to draw attention to his identification of the rocks as belonging to the charnockite series.

In 1939 P. Legoux published a detailed description of the charnockites of le Massiv de Man on the Ivory Coast. He names the charnockite series "la serie magnésienne" but points out their close relationship to the charnockites of Holland's classic locality of Madras. Legoux writes (Legoux, p. 30): "Il est classique de comparer la série à hypersthène de Man aux roches de l'Inde, connue sous le nom de charnockites. Nous verrons que certaines différences apparaissent au point de vue minéralogique et pétrografique, à côte de frondes analogies. Le géologue de terrain peut également relever des ressemblances frappantes". All the different divisions are represented, "charnockites stricto sensu, la série intermédiaire, la série basique" and "la série ultrabasique". Legoux comes to the conclusion that the charnockitic series of the Massiv de Man cannot represent an intrusive series of differentiated igneous rocks. He ascribes the origin to the "érection de puissantes chaînes de montagnes et granitisation de leurs racines les plus profondes, puis poussées tardives à un moment où l'activité magmatique s'est éteinte" (p. 29). In the concluding lines of a chapter "Comparaison avec les roches à hypersthène de l'Inde", he says: "A la lumière de faits qui étaient à l'époque où il (Holland) écrivait, nous sommes portés à interpréter ces descriptions en faisant appel à des phénomènes de migmatitisme. Quoiqu'il en soit, les observations que nous avons pu faire, avant même de connaître les travaux de l'Inde, rappellent les descriptions qu'il avait publiées de façon souvent étrange et cela suffit à marquer la parenté profonde des deux provences que nous avons essayé de mettre en parallèle. Une différence subsiste néanmoins: Holland considère comme certain le charactère intrusif de la charnockite; en Côte d'Ivoire, la série magnésienne n'est qu'une forme différenciée du fond granitique". (Legoux, p. 31).

Legoux states (p. 30) that he had not at his disposal any literature regarding Peninsular India other than Holland's Memoir of 1900. He was therefore not acquainted with the results of more recent researches in India as regards conclusions on the origin of the charnockites. I have cited his paper partly because it will be but little known, partly to show that as a result of his own field work, he too has independently come to the conclusion that the charnockite series of the Massiv de Man, evidently representing a group of typical charnockites, cannot represent intrusions of differentiated igneous rocks in situ.

From a more southerly part of Africa, GEVERS and DUNNE have given a detailed description of "Charnockitic Rocks near Port Edward" in Natal (Gevers and Dunne, p. 183). The series comprises only acid and sub-acid types. As a result of their investigation, the authors come to the following conclusion (p. 212): "The picture thus suggested is somewhat as follows. A group of highly metamorphic ancient rocks, comprising granulites, biotite-schists and marbles, was folded at depth along E-W axes. Contemporaneous with this upheaval, mostly towards its closing stages, came the intrusion of the 'old granite'. In certain zones of great depth granite magma caused migmatitisation or anatexis and also more extensive and even complete palingenetic fusion of the rocks of the pre-existing ancient complex. · · · The biotite-schists were largely assimilated to form highly biotite zones in the granite. In the vicinity of garnet- and pyroxene-granulites, including ancient hypersthene-granulites of mixed origin, the advance of the 'migmatitic front' either produced hybrid charnockites of the type described as occurring along or near contacts, or, by a process of complete palingenetic fusion and progressive granitisation, the normal charnockite rocks, now found farther away from the contacts. Needless to say, it is not suggested that the normal charnockites were in their entity produced by a simple process of fusion and subsequent crystallisation of pre-existing hypersthene-granulites. The process visualised is one of palingenesis and widespread granitisation, varying in intensity from place to place".

In the Arendal region of south Norway, recently described by JENS BUGGE, there is no doubt that charnockitic rocks in typical development, both in regard to mineralogical composition and chemical variation, are represented. In this case it is, together with the Varberg series, one of the few areas in Europe of representative rocks of the charnockite series.

In this connection I shall only touch upon Jens Bugge's view as to the origin of his rocks. In his first paper (J. Bugge 1940, p. 88) he writes: "It is interesting that the arendalite (Bugge's name for his charnockite series of the Arendal district) sometimes shows eruptive character indicating a magma which has forced its way upward, pushing the other rocks away, while at other places, especially in the south-western part, it continuously passes into the banded gneisses". In a later publication (J. Bugge 1943, p. 141—142) Bugge says: "I have proposed 'arendalites' as the name for a series of rocks of noritic-charnockitic character, situated between Arendal and Risør. They show a great resemblance to the charnockite rocks of India, Ceylon, Uganda, etc. and are regarded as migmatite rocks. Both the geological investigations in the field and the microscopic investigations show that the arendalites cannot have been formed from a homogeneous melt, but by a metasomatic transformation of a pre-existing rock complex. The relict structures also show that the transformation must have taken place somewhat in situ. This is especially the case of the western parts; the rocks of the eastern[1] showing a more transgressive character. · · · No metatect occurs next to the rock component; the metasomatism, however, has taken place by the soaking of the rocks in a disperse mobile solution (an ichor). The metablastesis may be called an arendalitization. · · · The arendalites were formed under the highest PT conditions attained in Sørlandet and as regards their mineralogical composition they correspond to the granulite facies". In a subsequent paper (J. Bugge 1946, p. 32—38) Bugge first recapitulates verbatim the quotation given above. After a detailed discussion of the mineral reactions "definitely demonstrated and ascertained by microscopic studies of thin slides", he continues: "From such considerations I have concluded that the formation of the arendalites chiefly took place by reaction and diffusion in the solid state. · · · The surrounding gneisses gradually pass into arendalites while the rock minerals are replaced by those characteristic of the arendalites. · · · The magmatic character sometimes exhibited by the arendalites must be explained by the effect of exothermic reactions during the homogenization, causing a local heating of the rocks as compared to the surrounding rocks" (p. 38).

I have had an opportunity of visiting the Arendal district under the kind guidance of Carl Bugge. I was then able to verify the absolute conformity in appearance between the rocks from Arendal and those from Varberg. Many specimens collected from the eastern, "more transgressive" parts at Arendal could not be distinguished from corresponding Varberg rocks, when later compared with one another. One can therefore hardly anticipate different modes of origin for the rocks of the two localities. A presumption that the rocks in the western part of the Arendal district only verged upon the plutometamorphic zone and therefore were only partly subjected to charnockitisation in the form of a lit par lit saturation of susceptible layers of the banded gneiss would be in conformity with Bugge's observations. The "more transgressive character" farther to the east would signify a plutonic mobilisation, representing parts which had attained complete fluidity, culminating in a magma capable of moving bodily upwards.

In the Antarctic and Arctic hemispheres presumed charnockitic areas are situated in such inaccessible regions that only stray observations and collections from isolated points have afforded a basis for description and discussion. However it seems evident that rocks from the Antarctic continent belonging to the charnockite series must form an important and widespread group between c. 45° E and 140° E. STILLWELL has described rocks definitely belonging to the charnockite group from Adelie Land, NOCKOLDS from Queen Mary Land and TILLEY from Enderby Land, all localities between the longitudes given above. It is of a certain interest to note that, from all three districts, intermediate charnockites seem to be unrepresented. Nockolds and Tilley only mention ultrabasic, basic and acid types, and in Stillwell's description only acid and basic types seem to be dealt with. As in other regions of charnockites the intermediate group often predominates, its apparent absence from the Antarctic region is worthy of notice.

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[1] east and west reversed by Bugge in this place.

Both Nockolds and Tilley base their descriptions on specimens collected by members of two different expeditions, whereas Stillwell's specimens were collected by himself. It is natural that the conclusions, of necessity drawn from fragmentary material, cannot be very decisive, but all the three authors mentioned have given their opinions in regard to genetical problems, based on the descriptions of their material. Their conclusions may therefore be given summarily.

Stillwell writes: "We think it impossible to deny the metamorphic character of these acid hypersthenic rocks, and yet we find that they correspond very closely with the description of the hypersthenic rocks of Peninsular India, which have been called the charnockite series. · · · But the charnockites have been considered by Holland to be igneous rocks, which have consolidated under phenomenal conditions. Can then these Antarctic metamorphic rocks be strictly compared with igneous rocks, or is it possible that the charnockites are really metamorphic rocks? It behoves us to critically examine the evidence" (Stillwell, p. 192).

I must refer to Stillwell's paper regarding his critical examination (p. 193), of which much refers to the linear arrangement of the constituent minerals. He concludes as follows: "Holland's interpretation of the foliation and banding has produced the chief difficulty in the determination of the charnockites as metamorphic rocks. If this difficulty be removed there is no barrier to the interpretation of the charnockites, like the Antarctic rocks, as a suite of igneous rocks that have suffered complete recrystallisation under the conditions of Kata-zone metamorphism. The demonstration of the primary igneous character by the form and structure of the great massive, by the existence of dykes and apophyses proceeding from the main mass and by the presence of included fragments of foreign rocks is unaffected by the acknowledgement of Kata-zone metamorphism. Nor is the chemical and mineralogical evidence affected. Recrystallisation under Kata-zone conditions (high uniform pressure, dominating largely over stress and high temperature) does not destroy the dominating igneous structures · · · ·" (p. 194).

As may be seen, Stillwell is inclined to ascribe the origin of the charnockites of Adelie Land to a deep-seated metamorphism of a series of primary igneous rocks.

NOCKOLDS begins by quoting Stillwell concerning the origin of the charnockites of Queen Mary Land. He writes as follows (Nockolds, p. 51): "Stillwell believes the series (charnockite series of India and from Adelie Land) to be of metamorphic origin, derived originally from dolerite (the basic members) and granite (the acid members), whereas Holland looks upon them as igneous rocks consolidated under rather abnormal conditions. Without going fully into the question, because the rocks of this series, described in the present report, offer no definite evidence either the one way or the other, it may be remarked that if the rocks consolidated in their present condition from a magma, the presence of hypersthene in the acid as well as in the basic members, shows that the magma was poor in volatile constituents. · · · Moreover, the fact that the chemical analyses of the charnockite series bear a close resemblance to those of normal igneous rocks, does not either prove or disprove their metamorphic origin. They may quite well be heteromorphs, due to consolidation under different physical conditions. One of these conditions, as we have seen, must be relative poverty in volatile constituents, another probably high pressure. Under these conditions, they might come to resemble Kata-zone metamorphic rocks rather strongly''.

Finally I come to TILLEY's description of specimens from Enderby Land. Regarding the origin of the charnockitic rocks, he says: ''The charnockite series includes ultrabasic — acid members. The basic and ultrabasic members of the series show evidence of metamorphism, and it is to be noted that two of them occur as irregular bands suggestive of inclusions in the typical Proclamation Island rock. The metamorphism observed is consonant with the changes expected on reheating by intrusion by later members of the series'' (Tilley, 1937, p. 15). No further references to the origin of the rocks is made except when, with regard to the perthite and antiperthite textures, Tilley says: ''This might be accounted for by consolidation of a comparatively dry magma, crystallization being arrested at a high temperature due to the paucity of water in the magma'' (p. 15).

From the arctic regions RAMBERG records rocks of a charnockitic nature. He says: ''My work on the pre-cambrian of western Greenland shows that the hypersthene gneisses (enderbitic gneisses) and the noritic rocks there must be interpreted in the same way as the hypersthene gneisses in Uganda. · · · The noritic components in the hypersthene gneiss are, therefore, derived from the common diabases. The hypersthene-bearing enderbitic gneiss that commonly includes and penetrates the noritic layers is an activated granulitic facies variety of the old hornblende-biotite gneiss which once was invaded by the diabase dykes. · · · These field observations show that the rocks of charnockitic affinity (norites, enderbites, charnockites) were not formed by magmatic differentiation but by high grade regional metamorphism'' (Ramberg, p. 35).

The description of the rocks from Ellesmere Land by CARL BUGGE hardly gives enough details regarding their field connections to permit of a decision as to whether they are true representatives of the charnockite series. The conformity has chiefly been assumed on chemical affinities (Carl Bugge, p. 19—20).

The above review of different opinions advanced in descriptions of rocks belonging to or assumed to be connected with the charnockite series in respect of their origin or metamorphic development, does not claim to be complete. Reference has only been made to works of classical importance or modern trend, in which the petrogenetical evolution of the rocks has been discussed, or in which questions relating to the charnockitic problem at large have been commented on.

Before drawing any conclusions from the opinions quoted above with reference to the petrogenetical problems of the Varberg series of charnockitic rocks, I should like to draw attention to some other varieties of rocks which, either from a theoretical point of view or from field connections, have been taken as syngenetic with the charnockites. I allude to the occurrence of rocks which have been named leptynites and granulites, to certain eclogitic types, to the recurrent presence of an aplitic granite and to the association of anorthositic rocks with the charnockites.

In his memoir on the evolution of the metamorphic rocks, F. J. TURNER has subdivided the rocks referable to the granulite facies into five groups, of which the first four are of interest in this connection. They are characterised by the following mineralogical assemblages:

Quartz — orthoclase — garnet (-plagioclase-sillimannite or kyanite). The khondolites of Southern India are referred to this division, as well as, in part, the granulites of Saxony.
Quartz — orthoclase — hypersthene (-garnet-plagioclase). This group is said to represent "the normal assemblage found in charnockites".
Plagioclase — hypersthene — garnet (-quartz-orthoclase)
Plagioclase — hypersthene — diopside (-quartz-orthoclase)
The two last assemblages are taken to represent the pyroxene-granulites and the noritic members of the charnockite series (Turner, p. 101).

The granulites of Northern Finland have been considered to be associated with charnockitic rocks. Under the heading "Petrologischer Überblick über die Gesteine der Granulitformation" (in Finnish Lapland), SAHAMA subdivides the rocks of this formation into six divisions, of which two are referred to as representing rocks of charnockitic charncter. Sahama writes as follows: "Ausser denjenigen Gesteinen, die in der finnisch-lappländischen Granulitformation wohl under dem Namen Granulit vereinigt werden können, hat man dort eine ganze Menge von Typen vor sich, die offenbar einer gesonderten Bezeichnung bedürfen. Es sind vor allem die pyroxenführenden Glieder der Granulitformation in Betracht zu ziehen, die zum Teil auch Granat enthalten und eine granitische bezw. granodioritische bis gabbroide Totalzusammensetzung zeigen. Derartige Gesteine sind zum ersten Mal von Holland (1900) und dann später von Washington (1916) und Groves (1935) mit der Bezeichnung Charnockit-Serie belegt worden, wobei die sauren Typen als Charnockite, die basischeren hingegen als Norite benannt worden sind. Die pyroxenführenden Gesteine der vorliegenden Granulitformation zeigen zwar in der mineralogischen Zusammensetzung deutliche Analogien mit den Gesteinen dieser Charnockit-Serien, besitzen aber in ihrer Structure gewisse Züge, die den typischen Charnockiten und Noriten fremd sind" (Sahama, p. 12). These types Sahama names Charnockitgranulite and Noritgranulite.

I have cited the above authors to indicate that a connection has been assumed between the normal granulites of the granulitic formation in general and rocks belonging to the charnockite series. This has evidently been presumed on account of a related metamorphic development, inasmuch as they have both been taken as belonging to Eskola's granulite facies and, furthermore, because of the occurrence of hypersthene in many rocks associated with normal granulites. However, in the granulite formation the typical xenomorphic granular texture is so often combined with a banded structure, indicating the co-operation of directed stress in contrast to the only occasional granulose flow structure in the charnockitic rocks, that a difference in their metamorphic evolution seems obvious. Though certain mineralogical and textural similarities indisputably occur, I am not convinced that many hypersthene-bearing rocks in association with typical granulites are to be reckoned as genetically referable to the charnockite series. I hesitate to accept the Charnockitgranulite of Sahama from northern Finland as well as the rocks named charnockites by PARRAS from Uusimaa and by ANNA HIETANEN from the Turku district, both in southern Finland, as belonging to the charnockite group stricto sensu. Obviously rocks similar to those of Hietanen occur on the petrologically corresponding Swedish side of the Bothnian Gulf, but Sundius has simply referred to them as hypersthene-bearing syenites.[1]

From the typical charnockite regions in India several rocks of more or less granulitic character have been reported and discussed.

In many places in his memoir Holland mentions the occurrence of leptynites in close association with the rocks of his charnockite series. They are, however, said to represent crushed rocks, owing to 'dynamic action' (Holland p. 173). I may quote a passage confirming his opinion in this respect. "· · · · a further occurrence of leptynite in association with charnockite shows a gradual passage from the former to the latter. This occurs on both sides of the central mass of norite which is thus encroached by leptynite and charnockite. The fact revealed at this point leaves little doubt as to the secondary origin of the characters which serve to distinguish the leptynite from normal charnockite" (Holland, p. 174. cf. also Fig. 4 and 5 in the memoir). The leptynite is described by Holland as follows: "· · · · a friable, cream-coloured rock which is sprinkled with garnets. The signs of dynamo-metamorphism, so evident in the field, are confirmed by an examination of this rock under the microscope. The proportion of quartz to microcline and opaque iron-ores is the same in this rock as in the unaltered charnockite, but instead of hypersthene we have about an equal quantity of irregularly shaped pink garnets" (Holland, p. 142 -145). Leptynites of this character have no counterparts within the Varberg field. If the interpretation that their origin is due to dynamic action is correct, this is natural, since metamorphic processes of this type are not met with in this area.

In several places in his memoir Rama Rao mentions "fine-grained granulitic types" (Rama Rao, 1945) or "siliceous granulites of different colours" (p. 106). On page 80 he says: "Somewhat different in texture and appearance to · · · · the coarse-grained granite types (charnockites sensu stricto) and associated with them, and often grading into them in the field without clear-cut boundaries, are found in the larger belts of the charnockite series of the Biligirirangan Hill range, fine-grained granulitic siliceous schists or gneisses which, when containing hypersthene, resemble the typical acid charnockites and have been mapped as such." So far the description might intimate similarities to the felsic charnockites of the Varberg series, but when in what follows he shows them interbanded with garnetiferous siliceous leptynites and exhibiting mylonitic textures, the relationship becomes more vague. However, in part they have evidently been mapped as belonging to the charnockite series.

Tilley classes the rocks from Proclamation Island under the two headings: those belonging to the charnockite series (as the typical rocks of the island) and garnet granulites. He says furthermore: "though referred to as granulites they do not possess the strongly foliated structure characteristic of the granulites of Central Europe, nor have they the characteristics of the garnetiferous granulites (leptynites) associated with the charnockites of Madras". The rocks are described as granular massive rocks of a gray colour. "Under the microscope the constituents are seen to be quartz, clouded brown due to fine inclusions, and composite felspar, the colour of which is given by the fine dense intergrowth of two felspars, though these also contain numerous dustlike inclusions." Tilley does not draw any definite conclusions regarding the relationship between the rocks of definitely charnockitic character and the granulites as "there is unfortunately lack of important data as to the field relations of these rocks" (Tilley 1937, p. 8 and 15).

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[1] Berggrundskarta över Stockholmstrakten. Sv. Geol. Undersökning, Ser. Ba No. 13, Stockholm 1946.

It is evident that rocks corresponding in many respects to the felsic charnockites of the Varberg district in respect of more or less complete absence of pyroxene minerals or femic minerals in general, have been recorded from other typical regions of charnockite rock assemblages. Their petrological position in relation to the adjacent charnockitic rocks has, however, been interpreted in different ways or has been left an open question.

In this connection it may be observed that both Ghosh and Rama Rao mention rocks of eclogitic type in connection with rocks of the charnockite series. Ghosh writes: "At the ultrabasic end, the rocks of this area (the Bastar State and western Jeypore) have been found to pass into eclogitic rocks with a variable proportion of hypersthene in addition to the minerals found in eclogites. Under the heading "Ultrabasic types of charnockites" Ghosh further mentions an eclogitic type and states: "This type is coarsely crystalline and schistose, with a dominant greenish colour, the prevailing colour being due to the presence of omphacite and smaragdite. A little pink garnet and greenish and brown-yellow spinel (pleonast) are also noted. The type is rare and has been found only in a few places · · · associated with diopside gneisses and diverse types of charnockites." (Ghosh, p. 6 and 14.).

Rama Rao also mentions eclogites under the heading "olivine rich types" of the ultrabasic division of the typical charnockite series. He says: "In some of the hand specimens of these rocks, if based purely on the mineral composition, the garnetiferous melanocratic portion may be termed eclogites whereas the leucocratic portions can be called garnetiferous hypersthene or hornblende granulites or basic or intermediate charnockites according to their texture and other characters". In this connection reference may also be made to DAVIDSON's discussions of connections between charnockitic metagabbros and eclogites" (Davidson, p. 103.).

From these quotations it is evident that rocks belonging to the charnockite series have been found to occur in connection with, on the one hand, rocks which have been referred to as granulites, on the other hand to rocks of eclogitic type, both exhibiting in their composition and development many of the characteristic features of these metamorphic groups.

When Eskola says that the granulite facies occupies a position intermediate between his hornfels and eclogite facies (Eskola, p. 363), one might, from the field connections indicated above, speculatively refer the typical charnockites to a charnockite facies, intermediate between the granulite and the eclogite facies.[1] Many charnockitic rocks, however, contain considerable amounts of biotite and hornblende, minerals which would be inconsistent with such a facies. In metamorphic rocks, however, one can in general hardly take it for granted, that equilibrium between the reacting minerals has always been reached. Therefore in their more complex mineral association many rocks referred to the charnockite series may be ascribed to several facies, which they have transgressed during their metamorphic evolution. Only such rocks of the charnockite series as have attained a stable mineral composition, could be described as belonging to a definite charnockite facies. These rocks would be characterised by the circumstance that pyroxenes and garnet constitute the only femic minerals of importance. When biotite and hornblende enter the rocks together with pyroxenes and garnet, or to any great extent replace them, these minerals would indicate that, during the metamorphic evolution, an equilibrium has not been completed. The different constituent minerals in the rock would then point to transgressions through different metamorphic stages. They may represent relics of a previous metamorphic period or a commencing stage of the charnockitic transformation or new-formed minerals of a terminating metamorphic period.

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[1] Schüller has already temporarily used the term "charnockite facies" without, however, discussing its petrological position. (Schüller, p. 583, 585).

It is of interest to note that the occurrence of younger granites, often of aplitic character, in close association with rocks belonging to the charnockite series, has been reported from a number of different localities, both from the Indian charnockite area and from other regions.

Holland in his classic memoir mentions in several places "quartz-felspar rocks associated with charnockites". I may quote what he says in an introduction to the description of these rocks. "Although, on account of the absence of hypersthene these rocks would not, if found isolated, be recognised as members of the charnockite series, yet on account of the facts that they occur as veins in normal charnockite and are composed of the same blue quartz crowded with minute hairlike inclusions together with a beautifully microperthitic microcline, they must be considered to be as much genetic relatives of the charnockites as the common acid contemporaneous veins which in granites have always been regarded as the results of the final consolidation of the magma which gave rise to the main masses of the rock they run through." In the quotation given above Holland speaks only of veins, but lower down on the same page (Holland, p. 145) he says: "Larger masses of rock having a similar mineral composition are exposed within the immediate neighbourhood, and in the absence of evidence to the contrary should be regarded as members of this series. The mass of rock out of which the remarkable Seven Pagodas have been hewn in situ, is also almost wholly made up of quartz and microperthitic felspar". It is evident that a rock of alaskitic composition — i.e., of the same chemical composition as the aplitic granite of the Varberg district, takes part in the charnockitic assemblage at Madras.

If we turn to other recent publications on the rocks of the charnockite series, we find repeated mention of observations regarding the occurrence of a younger granite in association with them.

In his interesting paper on "a possible relationship between the charnockites and the Dhawars" Vredenburg says that the Closepet-Channapatna granite consists to quartz, microcline, zoned plagioclase, biotite, accessory zircon, apatite and magnetite. He observes further: "It will be noticed that this composition is exactly that of the average gneissose Fundamental Gneiss from which it does not seem therefore to be separable as a truly distinct formation. It represents perhaps a zone amidst the general spread of biotite-gneiss of the Peninsula which subsequently to its primitive consolidation has become fused and active. If we accept the latter relationship, it is conceivable that, even where intrusion is not observed on the large scale, considerable impregnation of acidic material may have affected the (Coimbarore) charnockites, and in the same fashion may, perhaps, prove true of other charnockite areas. If any confirmation were found to the above outlined suggestion, the metamorphism which has originated the charnockites is partly or largely a result of acid impregnation, the intermediate forms of charnockite would have to be regarded as somewhat of the nature of hybrid or rather syntectic rocks." (Vredenburg, p. 444.).

Rama Rao writes: "The chemical and norm composition of the acid charnockites of Mysore are almost similar to those of their associated garnetiferous quartzites and biotite gneisses and resemble to a considerable extent those of fine-grained pink granitic types of the younger (Closepet) granites" (Rama Rao 1945, p. 103.).

In his paper "The Archaean Complex of Mysore" Rama Rao already in 1940 says: "The charnockite rocks do not form a separate granitic intrusion. They are the reconstruction phases of older rocks, formed as an effect of intrusion of the younger series of Closepet granites" (Rama Rao, 1940, p. 81.). Analyses are given of an acid charnockite and of 'the newer Closepet granite' (p. 95), showing a similar chemical relationship to that found between corresponding analyses of a felsic charnockite and the aplitic granite from the Varberg field. I have reproduced a part of Rama Rao's map from the publication quoted (Map I), which shows a distribution in the field of the different types of the charnockitic rocks and of the Closepet granite, which in nearly every detail tallies with that of the corresponding rocks around Träslövsläge (Pl. VI). The dominating part occupied by the aplitic granite within the Varberg district and by its counterpart within the Mysore field seems to indicate a close petrogenetical relationship in respect of the origin of the two rock complexes (Fig. 35).

Recapitulating his observations in a concluding paragraph Rama Rao says: "Most of the acid and intermediate types have originated from various processes of assimilation by the younger granitic intrusives and also from reciprocal reactions between the two series of the invaded and invading rocks" (Rama Rao 1945, p. 163.).

From the Baster State of India Ghosh also mentions the occurrence of an aplitic granite in close association with the charnockite rocks. He says (Ghosh, p. 40): "At the Yapala occurrence as elsewhere, the basic charnockite has been invaded by a granitic or aplitic magma; the latter rock may be garnetiferous or not and is occasionally diopsidic and rarely hypersthenitic. This passes into a leucocratic, even-grained aplite, practically free from ferro-magnesian constituents". I may remark that these lines of Ghosh as well as those of Vredenburg, quoted above, might equally well refer to conditions within the Varberg district. On p. 52 Ghosh further comments as follows on the significance of the aplitic granite: "It has been mentioned that hypersthene-granite grades into diopside granite and then into a normal aplitic rock without diopside. In a medium of a highly alkaline fluid, hypersthene is unstable and breaks down directly into biotite or through the intermediate stages of diopside and hornblende. Such a breakdown of hypersthene has been noted in the case of charnockites under magmatic influence. The diopside aplites and diopside-hornblende aplites thus represent progressive stages in the process of de-hypersthenenisation."

If we pass to regions of charnockites outside India, we again find the occurrence of an aplitic granite mentioned in close connection with the rocks of the charnockite series from the Ivory Coast. Legoux describes, under the name 'aplogranites', an aplitic granite with the mineral composition given as follows: "Ces roches sont de constitution assez simple, puisque les deux éléments essentiels en sont quartz et un feldspath potassique. Ce dernier est tantôt le microcline. · · · On peut remarquer la paranté de ces paramètres avec les charnockites. Nous pouvons donc, bien que la roche ne manifeste pas d'hypersthène à cause de son charactère hololeucocrate, la considérer comme le terme extrème de la série granitique magnésienne." (Legoux, p. 42 –44.). La série magnésienne is the name by Legoux for his charnockite series.

These quotations will suffice to show that the occurrence of an aplitic granite

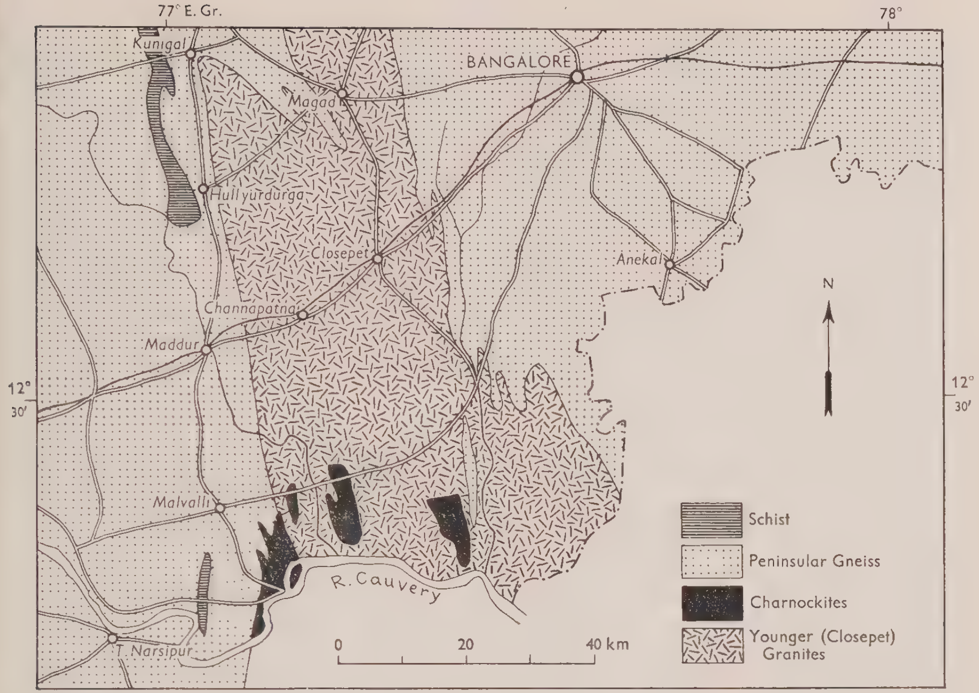

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Fig. 35. Field distribution of charnockite and 'younger granite' in Mysore (after Rama Rao, Mysore Geol. Survey, Bull. 17, map I).

in close association with charnockitic rocks is not of unusual occurrence and in many cases it has been interpreted as a later activated facies, which not only invaded but also to a greater or lesser degree contaminated the charnockitic rocks. In this connection the question of the syntectic nature of the intermediate charnockites has repeatedly been brought up for discussion (Ghosh, p. 2., Gevers and Dunne, p. 212., Jens Bugge, 1943, p. 141).

Anorthosites and associated labradoritic rocks have in many cases been combined genetically with rocks presumed to belong to the charnockitic series. This may perhaps to a certain extent be due to the fact that Rosenbusch classified them together as a "Charnockit-Anorthositreihe" (Rosenbusch, Elemente 1910, p. 183). I allude to the rocks of the Egersund and Bergen districts as well as to certain occurrences in U. S. A. and Canada. Holland himself accepted the Egersund[1] rocks as appertaining to the charnockite family, relying on J. H. L. Vogt's summary description of the area in 1893 (Holland, p. 135).

Inasmuch as the rocks of the charnockite series are presumed to have originated as the result of a plutonic metamorphism, a genetic association with anorthositic rocks would hardly be anticipitated. Balk, referring to the anorthosites of the Adirondacks, presumes that "the effect of volatiles in the anorthosite massif is perhaps greater than might seem apparent at first" (R. Balk. Journ. of Geol. Vol. 52, 1944, p. 300). If this assumption should be found maintainable for anorthositic rocks in general, the consanguinity of anorthosites with the charnockites, universally now admitted to have been formed under exceptionally dry conditions, would hardly be plausible.[1]

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[1] previously spelt Ekersund.

The petrological milieu of the presumed charnockitic rocks, associated with the labradorites of the Bergen district, cannot be said to be representative for the charnockite series, so definitely restricted to metamorphic regions, where protracted deep denudation has exposed the most ancient rocks of the continents. The rocks there referred to as appertaining to the charnockite series do not, either in outward appearance or in texture or mineral composition, in any respect coincide with the very uniform development of typical charnockites, from wherever they originate. In his earlier descriptions of the labradorite rocks from western Norway C. F. KOLDERUP named the types containing an orthorhombic pyroxene mangerite and birkremite.[2] I think it advisable for the present to retain these names for the hypersthene-bearing rocks of the Bergen district without alluding to connections with the charnockite series. Though Goldschmidt has referred them to an "anorthosite-charnockite group" he observed in the same connection that these rocks "in Faltengebirgen keineswegs häufig vertreten sein können und dass noch in keinen anderen Gebirgen ein zwingender Beweis für ihre Intrusion während der Faltungsperiode erbracht ist." (Goldschmidt, p. 136.).

The Egersund area is situated in a different petrological milieu, which in itself would not gainsay that definite charnockitic rocks may not have originated there. Specimens from Farsund coincide in their outward appearance in every respect with the charnockites from Arendal and Varberg and the mineral composition is found to be similar to that of an acid charnockite. BARTH says in his paper Geological map of western Sørland: "In my opinion farsundite and birkremite represent closely related derivatives of a deep-seated magma that some time after the conclusion of the pre-cambrian orogeny rose from a deep center in the neighborhood of Farsund-Lista, and by metasomatic alteration, brecciation, disintegration and assimilation invaded the country gneisses, thus forming with them injection gneisses and migmatites. · · The relations of anorthosite (in the area) are still uncertain." (T. F. W. Barth. Norsk Geol. Tidskr. Vol. 25, 1945, p. 8.). It may be worthy of notice that Barth uses the name birkremite for the hypersthene-bearing granite of the district without any allusion to relationship with the charnockitic rocks. The affinity of the hypersthene-bearing rocks of the Egersund district with the charnockite series, sensu stricto, will for the present be left an open question.

With reference to the charnockite area in Greenland RAMBERG says: "The vast massivs of anorthosite, however, so typically connected with some charnockite provinces, do not occur in the hitherto mapped part of Greenland. In this respect the Greenland complex is similar to the classic Indian area, the complex of Uganda, Africa, the charnockitic affinity in Ceylon and similar rocks in the Kongsberg-Bamle formation." (Ramberg, Econ. Geol. Vol. 43, 1948, p. 554). The genetic connection between vast massivs of anorthosite and "some charnockite provinces" is at present questionable. The regions referred to by Ramberg as similar to the Greenland complex are just those in which the most typical rocks of the charnockite series are represented and which have been taken as type localities for the authentic charnockites, in the restricted sense applied in this paper. Rocks belonging to the anorthosite group can therefore not be said to be representative for those regions. Where they have been recorded, they only seem to represent incidental leucocratic segregations, in conformity with what has been anticipated within the Varberg area. A specimen from Pallavaran, Madras, represented in my collection of charnockitic rocks from different continents, is labelled a "coarse felspatic vein in charnockite". This vein is very similar to the leucocratic segregations in the Varberg field (cf. p. 253.).

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[1] The role of volatiles in connection with anorthosites has previously been intimated by Alling and by Buddington. (Alling, Journ. of Geol. Vol. 40, 1932, p. 206. Buddington, p. 35).

[2] Die Labradorfelse des westlichen Norwegens. II. Die Labrodorfelse und mit denselben verwandten Gesteine in dem Bergengebiete. Bergens Museums Aarbok, 1903, No. 12, p. 109. — cf. also Kolderup, C. F. and Kolderup, N. H., p. 98.

Conclusions in respect of the petrogenesis of the charnockitic series of the Varberg district

As may be seen from the foregoing abstracts, much has recently been written on the presumed origin of the charnockitic series. Generally speaking nearly all more recent research on the subject tends to ascribe the formation of the charnockitic rocks to a deep-seated metamorphism of ancient rock formations of heterogenous origin. The chemical composition of the charnockite series must, then, be dependent on the composition of the surrounding rock complex. The mineral association has been taken to denote great uniform pressure combined with high temperature under exceptionally dry conditions during the metamorphic evolution. The intermediate charnockites have in many cases been interpreted as being of syntectic origin in the form of hybrid rocks.

I have tried to recapitulate somewhat in detail the views of different authors on the origin of the rocks belonging to the charnockite series in order to examine how far the conclusions we can draw in respect of the problem within the Varberg district tally with those arrived at in similar regions in other countries. In the following pages I shall now try to summarise the conclusions to which field work as well as microscopical and chemical investigations can lead us in respect of the petrogenetic evolution of the Varberg charnockite series.

The charnockitic rocks of the Varberg area are located within that ancient part of the Swedish archaean formations which has been subjected to long-continued denudation which has exposed rocks which have been submitted to a deep-seated metamorphism. This is in accordance with what has been emphasized as being the case in all regions where typical rocks of the charnockite series have been found to occur.

The mineral association of the rocks, composed of anti-stress minerals of high density and small specific volume, indicates a crystallisation under great uniform pressure at a high temperature and under exceptionally dry conditions. This must indicate that the metamorphic transformation took place at great depths. Of late the term plutonic metamorphism has been used for metamorphic processes under such conditions and has been adopted in this paper.

Chemical analyses have shown that some of the charnockitic rocks of the district are similar to rocks of the surrounding gneiss complex, the basic charnockites to the amphibolitic and gabbroic rocks, the felsic charnockite to the orthogneiss. The consequence would be that these types of the charnockitic rocks may well have been formed by a plutonic metamorphism of the heterogenous rocks of the surrounding gneiss formation.

If this assumption be accepted, we must look for another source for the origin of the intermediate types of the series, since no rocks corresponding in chemical composition are found within the surrounding formations. This does not imply that rocks of similar composition are not to be found within the Swedish archaean. As an example I may mention the Vaggeryd syenite, occupying an extensive area south of the lake Vettern. Its chemical composition is very nearly identical with that of an intermediate charnockite from Fästningsberget in Varberg. The relationship between the rocks is, however, restricted to the similar chemical composition. With regard to mineral composition and textural development, the Vaggeryd rocks retain the characteristic features of normal igneous rocks, but have none of the features characteristic of the charnockites of Varberg. This can only confirm that different types of the charnockite series may chemically be equivalent in every respect to rocks of normal igneous origin.

The question of the origin of the intermediate charnockites of the Varberg area presents a central problem, as they represent the most abundant types of the specific charnockites in the district. An indication as to the genesis may perhaps be found in the inconsistency of their chemical composition, in contrast to what we have found to be the case in other types of the Varberg series. This may lead to the conclusion that the intermediate charnockites do not answer to any definite petrographical unit. They have, as has been the case in so many other regions of the charnockite assembly of rocks, been interpreted here as hybrid rocks formed as a result of composite series of reactions between rocks of divergent chemical composition. These reactions may have been facilitated and accelerated by the participation of alkaline solutions emanating from the aplitic granite in connection with its palingenetic mobilisation.

It is difficult to say to what degree a presumed syntexis and hybridisation may have taken place in situ. The occurrence of only insignificantly contaminated xenoliths of the surrounding gneiss within the intermediate charnockites suggests that a certain displacement must have taken place. On the whole, however, observations in the field seem to indicate that a hybridisation, if such has occurred to any great extent, has not been combined with any more obvious change of position. If the basic charnockites in general have retained their primary intrusive position, the intruded rocks cannot be supposed to have been removed en masse. The consequence must then be that the rocks originally intruded by what are now represented as basic charnockites corresponded to the orthogneiss, now represented by intermediate charnockites. These probably attained their regenerated chemical and mineralogical composition in connection with reactions due to intergranular diffusion. The hybridisation may represent either an initial, an intermediate or a terminating stage in the metamorphic evolution of the charnockitic rocks, or most probably a consecutive process throughout the whole transformation period. An extended hybridisation, more or less in situ, need not gainsay that a certain degree of mobility of the hybrid rocks can have been attained in those parts of the rock complex where a partial fusion may have been achieved.

The aplitic granite would then remain as the only rock assemblage which in its entirety attained full palingenetic refusion. The effect of the aplitic granite on the other rocks may have been of a diversiform nature. Before reaching complete refusion, alkaline solutions from the acid granite, emanating from horizons above the zone of complete palingenetic fusion, may have actively influenced adjacent rocks, promoting assimilation processes already initiated within peripheral spheres of

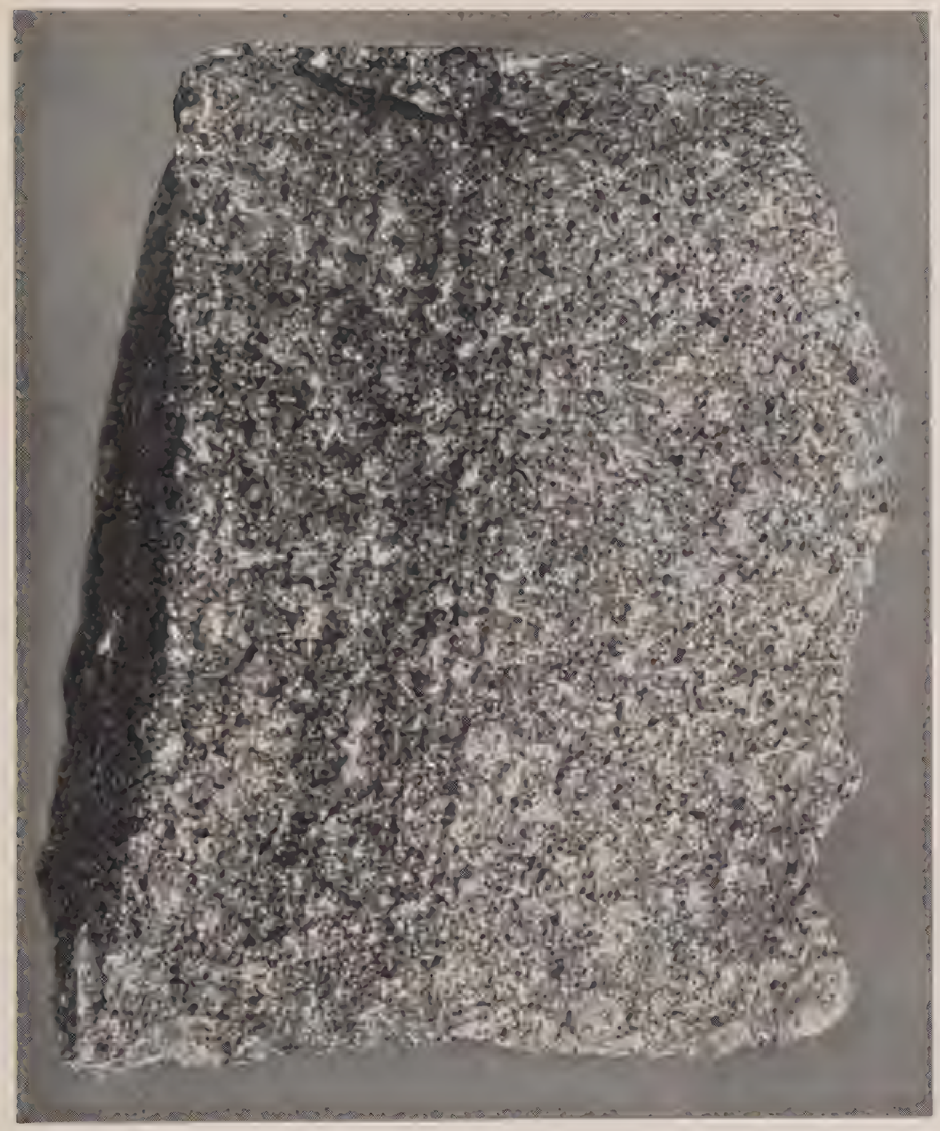

Fig. 36. Aplite granite in contact with hybrid rock. 1 × 1. Fladahalla quarry, Träslövsläge.

plutonic metamorphism. The first result might then have been the formation of relatively homogeneous rocks, though of unstable chemical composition. Subsequently the re-fused and mobilised acid granite invaded the rocks, already influenced in the direction of a progressing syntexis. This resulted in the formation of megascopically well-defined hybrid rocks (Fig. 36), amongst which some may even represent a "hybridism of second order", as defined by Harker (Harker, p. 196). I may in this connection again call attention to the fact that, down to the minutest detail, megascopically similar mixed rocks are found in the eastern parts of the Arendal charnockitic area, where, according to J. Bugge, the 'arendalites' show "a more transgressive character" (J. Bugge, 1943, p. 141).

If the foregoing assumptions can be accepted we may might be justified in drawing some conclusions as to the metamorphic sequence of the charnockitic rocks of the Varberg district. It will, however, be necessary to postulate that a mere corner of a larger area of charnockitic rocks is now exposed around Varberg. It would not be possible to assume that rocks restricted to a small area can have been submitted to a plutometamorphic recasting amid surrounding rock formations which have not partaken in the transformation. We shall therefore be obliged to assume that there exists a greater area of submerged rocks to the west or north-west, which has been involved in the different stages of plutonic metamorphism.

Accepting such a supposition, which necessarily must be of a speculative nature, the sequence of the different rocks belonging to the charnockitic series within the Varberg district would, according to field evidence, be as follows.

The basic charnockites are of primary igneous origin, derived from basic igneous rocks belonging to the archaean gneiss complex. Their often retained dyke-like aspect in the field, even if broken up into lenticular stretches, suggests that initially they were at least in part doleritic dyke intrusions, subsequently amphibolitisised in advance of the metamorphic changes leading to the formation of the charnockite series of rocks. In some cases, where the basic charnockites are more massive, they may represent more abyssal rocks of gabbroic character. In any case, it seems as if on the whole the basic charnockites retained their primary position in relation to the surrounding rock formations. The similarity in chemical composition seems to indicate heteromorphism between the basic charnockites and basic igneous components in the surrounding gneiss complex.

The intermediate charnockites, presumed to be hybrid rocks formed by the complete assimilation of rock components of different chemical composition, can hardly be assigned a definite position in the sequence of plutonic metamorphism. If their transformation to a great extent took place in situ, this process may have culminated in any period of the metamorphic epoch.

The felsic charnockites may in part represent the direct plutometamorphic transformation of the surrounding orthogneiss. As has been shown, the chemical composition of the two rocks may be almost identical. Some of the felsic charnockites may also represent a homogenisation of hybrid rocks, in which the aplitic granite is the mean ingredient with only an insignificant participation of charnockitic material, which then probably succumbed to stages of de-hypersthenisation on account of an alkaline influx from the aplitic granite.

The aplitic granite must be taken to represent a somewhat later intrusion of palingenetically activated portions of the surrounding gneiss. Its participation in forming the megascopically and microscopically hybrid rocks described above (p. 262), must indicate a penetration by such portions of the rock complex as have reached complete palingenetic fusion (Fig. 37).

In some rocks, especially of the intermediate charnockites, certain abnormalities in the mineral composition seem to indicate alterations of later date than the general plutometamorphic conversion. I allude to the occurrence of a bluish amphibole in some rocks, as well as to the sporadic occurrence of scapolite in the probably highly silicified basic charnockites from Björka-Tönninge. This secondary mineralisation may be explained by a casual and insignificant addition of volatiles during a sub-

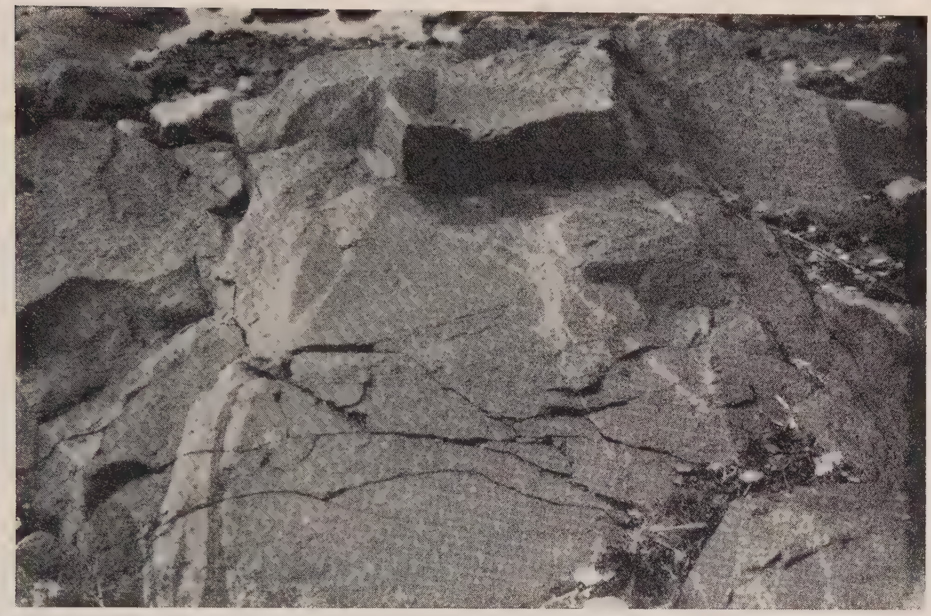

Fig. 37. Initial stage of hybridisation. Aplitic granite invading intermediate charnockite. Fladahalla quarry, Träslövsläge.

sequent upheaval to higher positions within the crust of the earth. The isolated occurrence of epidote and sphene in an intermediate charnockite from Fästningsberget in Varberg are indications pointing in that direction.

As is seen, the conclusions put forward above relating to the origin of the charnockite series of the Varberg district are in many instances of much the same character in their general import as has been presumed by Vredenburg and Groves, and later by Ghosh, Rama Rao and Legoux, concerning different areas of charnockites in India and Africa.

In this paper I have restricted myself to a description of the rocks within the Varberg area. It is not improbable that along the west coast, both to the south and to the north, the coastline may just include some further small outliers of a larger, presumably submarine, area of charnockitic rocks. I may mention some such possible localities.

In the description of the Survey map of Halmstad HJALMAR LUNDBOHM has noted that in the vicinity of the village Daggarp, about 75 km to the south of Varberg, rocks exposed in two small knolls are of an outward appearance similar to that of the then so-called "Varberg granite".[1]

During a casual visit in 1950 to Stenrör, north of Tylösand, I observed by the shore a quantity of large boulders of a rock almost identical with some of the hybrid rocks at Varberg. I was able to locate them as originating from a quarry at Haverdal some 10 km to the north.

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[1] Beskrifning till kartbladet Halmstad. Sv. Geol. Undersökning, Ser. Ab, nr. 12, 1887, p. 12

Table IX.

Analyses, molecular proportions, norms and Niggli values of all analysed rocks belonging to the charnockitic series of the Varberg area. The analyses are grouped according to increasing content of SiO_2.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	44.60	45.00	51.60	53.96	60.12	61.86	62.04	68.12	68.16	72.32	73.72
TiO_2	5.12	2.40	1.00	2.45	0.95	0.80	0.60	0.30	0.30	0.16	0.20
Al_2O_3	14.36	16.62	19.96	15.98	16.63	17.56	18.49	15.16	14.94	14.46	13.58
Fe_2O_3	5.73	6.05	7.06	2.76	2.19	1.24	1.65	1.48	0.98	1.24	0.60
FeO	11.64	8.97	3.60	6.16	4.79	4.03	1.50	1.69	2.24	0.67	1.12
MnO	0.20	0.31	0.16	0.27	0.10	0.06	0.08	0.05	0.10	0.02	0.02
MgO	5.89	7.24	3.04	1.58	0.82	1.87	0.87	0.73	1.12	0.33	0.14
CaO	8.72	9.50	10.44	5.82	3.75	5.00	2.04	2.40	2.56	1.78	1.04
Na_2O	2.15	2.76	1.80	4.18	4.73	4.00	4.49	2.85	3.02	3.39	2.43
K_2O	1.37	0.96	0.50	3.72	4.25	3.08	7.69	6.79	5.83	4.92	6.87
P_2O_5	0.00	0.00	0.50	1.85	0.77	trace	0.00	0.24	0.15	0.00	trace
Cl	—	—	0.10	—	—	—	—	—	—	—	—
$H_2O^{-105^\circ}$ ..	0.00	0.06	0.10	—	—	0.20	0.04	0.02	0.26	0.34	0.09
$H_2O^{+105^\circ}$ ..	0.14	0.16	0.48	0.27	0.25	0.70	0.52	0.25	0.44	0.50	0.18
	99.92	100.03	100.34	99.54	99.56	100.40	100.01	100.08	100.10	100.13	99.99
Sp. gr.	3.16	3.19	2.88	2.87	2.77	2.75	2.63	2.66	2.67	2.64	2.61

1. Basic charnockite. Lassabacka, north of Varberg.
2. Basic charnockite. Högahalla quarry, Träslövsläge.
3. Silicified basic charnockite, between Björka and Trönninge.
4. Intermediate charnockite. Apelviken, south of Varberg (with BaO 0.19, FeS 0.35).
5. Intermediate charnockite. Fästningsberget, Varberg (with BaO 0.21).
6. Sub-acid charnockite. Traneberg, Varberg.
7. Coarse-grained leucocratic charnockite. Träslövsläge.
8. Felsic charnockite. Högahalla quarry, Träslövsläge.
9. Hybrid rock. Bankahalla quarry, Träslövsläge.
10. Felsic charnockite. Himle station.
11. Aplite granite, Högahalla quarry, Träslövsläge.

Analyses Nos. 4 and 5 made by R. Mauzelius in 1880 for A. E. Törnebohm. The other analyses are new, made by Naima Sahlbom 1947—1949.

Quantitative System.

1.	III : 5 : 4 (3) : 4	Auvergnose	or : ab : an	15.61 : 35.13 : 49.26
2.	III : 5 : 4 : 4	Auvergnose	or : ab : an	9.65 : 38.42 : 51.93
3.	II : 4 : 4 : 4	Bandose	or : ab : an	4.70 : 23.07 : 72.23
4.	II : 5 : 2 : (3) 4	Akerose	or : ab : an	30.50 : 50.0 : 19.5
5.	II : 5 : 2 : 4	Akerose	or : ab : an	32.7 : 52.0 : 15.3
6.	II : 4 : 3 : 4	Tonalose	or : ab : an	24.98 : 46.37 : 28.65
7.	I : 5 : 2 : 3	Pulaskose	or : ab : an	49.91 : 41.72 : 8.37
8.	I : 4 : 2 : (2) 3	Toscanose	or : ab : an	55.15 : 33.15 : 11.70
9.	I : 4 : 2 : 3	Toscanose	or : ab : an	49.2 : 36.6 : 14.2
10.	I : 4 : 2 : 3	Toscanose	or : ab : an	43.64 : 43.08 : 13.28
11.	I : 4 : 1 (2) : 2 (3)	Omeose	or : ab : an	61.22 : 31.01 : 7.77

Table IX (cont.)

Molecular proportions of the analyses (× 100).

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	74.26	74.93	85.91	89.49	99.70	103.00	103.30	113.42	113.03	120.41	122.74
TiO_2	6.41	3.00	1.00	3.06	1.19	1.00	0.75	0.38	0.37	0.20	0.25
Al_2O_3	14.09	16.30	19.58	15.64	16.27	17.23	18.14	14.87	14.62	14.18	13.32
Fe_2O_3	3.59	3.79	4.42	1.73	1.37	0.78	1.03	0.93	0.61	0.78	0.38
FeO	16.20	12.48	5.01	8.57	6.67	5.61	2.09	2.35	3.12	0.93	1.56
MnO	0.28	0.44	0.23	0.38	0.14	0.08	0.11	0.07	0.14	0.03	0.03
MgO	14.61	17.96	7.54	3.92	2.03	4.64	2.16	1.81	2.78	0.82	0.35
CaO	15.55	16.94	18.61	10.38	6.69	8.91	3.64	4.28	4.56	3.17	1.85
Na_2O	3.47	4.45	2.90	6.74	7.63	6.45	7.24	4.60	4.87	5.47	3.92
K_2O	1.45	1.02	0.53	3.95	4.25	3.27	8.16	7.21	6.19	5.22	7.29
P_2O_5	—	—	0.35	1.30	0.54	—	—	0.17	0.11	—	—
Cl	—	—	0.28	—	—	—	—	—	—	—	—

Niggli values.

	si	*qz*	*al*	*fm*	*c*	*alk*	*c/fm*	*ti*	*p*	*k*	*mg*	*o*	*w*
1.	102.0	− 25.2	19.3	52.6	21.3	6.8	0.41	8.90	0	0.29	0.38	0.19	0.30
2.	97.1	− 31.3	21.1	49.8	22.0	7.1	0.44	3.81	0	0.19	0.47	0.20	0.37
3.	135.8	15.0	31.0	34.2	29.4	5.2	0.86	1.98	0.22	0.15	0.35	0.23	0.35
4.	168.8	− 12.0	29.5	30.7	19.6	20.2	0.64	5.77	2.45	0.37	0.24	0.21	0.28
5.	213.5	9.9	34.9	24.8	14.4	25.9	0.58	2.55	1.15	0.37	0.18	0.24	0.29
6.	215.7	34.5	36.1	24.9	18.7	20.3	0.75	2.09	0	0.34	0.39	0.47	0.77
7.	236.9	− 4.3	41.6	14.7	8.4	35.3	0.57	1.72	0	0.53	0.34	0.32	0.48
8.	305.6	78.8	40.2	16.5	11.6	31.7	0.72	1.08	0.54	0.61	0.30	0.30	0.42
9.	301.4	83.4	39.0	19.3	12.2	29.5	0.63	0.99	0.29	0.56	0.38	0.17	0.27
10.	383.7	147.3	45.2	10.6	10.1	34.1	0.95	0.64	0	0.49	0.25	0.47	0.62
11.	421.6	168.0	45.8	9.3	6.5	38.4	0.70	1.03	0	0.65	0.15	0.30	0.35

Norms.

	1	2	3	4	5	6	7	8	9	10	11
Q	—	—	14.96	3.90	7.26	11.84	1.17	19.74	20.03	29.50	30.31
or	8.08	5.59	2.95	21.68	25.02	18.20	45.41	40.13	34.47	29.05	40.57
ab	18.19	22.25	14.47	35.63	39.82	33.79	37.96	24.12	25.68	28.68	20.55
an	25.50	30.07	45.30	13.90	11.68	20.88	7.62	8.51	10.01	8.84	5.15
ne	—	0.70	sc. 0.16	—	—	—	—	—	—	—	C 0.27
di	14.43	13.67	2.49	2.57	1.89	3.23	2.00	1.51	1.61	—	—
hy	13.83	—	6.41	8.12	6.68	8.21	1.77	2.54	5.04	0.82	1.62
ol	1.71	14.20	—	—	—	—	—	—	—	—	—
mt	8.31	8.77	9.24	3.94	3.25	1.81	2.38	2.15	1.39	1.76	0.88
il	9.73	4.56	1.90	4.71	1.82	1.52	1.14	0.58	0.93	0.03	0.38
ht	—	—	0.69	—	—	—	—	—		—	—
ap	—	—	1.18	4.37	1.68	—	—	0.57	0.34	—	—
sal.	51.77	58.61	77.84	75.11	83.78	84.71	92.16	92.50	90.19	96.40	96.85
fem.	48.01	41.20	21.91	23.71	15.32	14.77	7.29	7.35	9.31	2.91	2.88

Some rocks, described by H. JOHANSSON from the Gothenburg region have certain abnormal features, which as Johansson says "have hardly otherwise been observed in any Swedish archaean gneiss".[1]

For the present these questions must be left open for further investigation.

A continuation of the Varberg field may be presumed further north in the Arendal district on the southern coast of Norway. The so-called arendalites of this region, described by Jens Bugge, are without doubt in part true charnockites. They would then represent a northern offshoot of a submarine area, partly in the form of a more metasomatic protruding front which has, according to Bugge's description, been the cause of a charnockitisation of bands in the banded gneiss of the district (cf. p. 300.).

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Colleagues and friends in different parts of the world have kindly sent me specimens of rocks belonging to the charnockite series, which have been very helpful in my comparative studies.

Mr ERIK HÖGBERG co-operated very efficiently in the field work during the summer of 1948.

During a temporary stay in Stockholm professor PAUL RAMDOHR of Berlin (now at Heidelberg) had the kindness to make a detailed examination of the ore minerals in some of the charnockite rocks (appendix 1.).

Dr STURE LANDERGREN has made spectrographic determinations of the minor constituents in all the analysed specimens of the Varberg rocks. He has kindly summarised certain conclusions thereon (appendix 2.).

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To all the above I beg to proffer my sincere thanks.

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For a survey of the regional distribution of charnockitic rocks, the literature, with the exception of papers referring to theoretical discussions advanced in part I, has been grouped according to geographical units. In general only those papers have been included in the bibliography in which, in connection with descriptions of the rocks or discussions as to their origin, the authors themselves have referred to the charnockite series. In some cases, however, where in connection with discussions on the charnockite problem direct reference to a paper has been made, such papers have also been included even if their authors do not themselves deal with the subject.

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APPENDIX I

Bemerkungen über den Gehalt der Varberggesteine an »Erzmineralien»

Von PAUL RAMDOHR in Heidelberg.

Einer Anregung von Herrn QUENSEL folgend untersuchte ich die Probe eines Varberggesteines auf ihren Erzinhalt. Da sich dabei enige überraschende Resultate ergaben, die noch dazu mit den früher von mir an einer Probe des als Ornamentstein in der Vorweltkriegszeit in Deutschland vielfach verschliffenen "grünen schwedischen Granits" erhaltenen keineswegs übereinstimmten, wurde ein etwas grösseres Material durchgearbeitet. Vorweg möchte ich meinem Freunde QUENSEL und *Svenska Institutet* dafür danken, dass sie mir bei der unvergesslich schönen Zeit im Sommer 1948 in Stockholm auch diese kleine Untersuchung ermöglichten.

Zur Verfügung standen etwa 12 Proben der gewöhnlichen Gesteine aus dem Varberggebiet, die im Folgenden näher gekennzeichnet sind, und drei Proben besonderen Charakters, die eine aus einem "Amphibolit"-Einschluss von Träslövsläge, eine aus einer etwa 1—2 cm dicken und mehrere dm² breiten Erzschliere von Träslöv-Hafen und schliesslich ein Gestein besonders reich an Granat. — Zum Vergleich lagen der Anschliff eines Plagioklascharnockits von Südkamerun, den mir Herr Dr. SCHÜLLER in freundlicher Weise zur Verfügung stellte und die Dünnschliffe von mir beschriebener typischer Orthoklascharnockite aus Mittelkamerun vor.

Der *Einzelbeschreibung* ist zunächst vorauszuschicken, dass die Erzmenge im Gestein roh parallel läuft mit dem helleren, bezw. dunkleren Aussehen und ebenso mit der Basicität der Gesteine, dass aber in Anbetracht der geringen Gehalte an Fe_2O_3 und FeO der Erzgehalt stets erstaunlich hoch ist, jedenfalls höher als er einer "normativen" Berechnung entspräche. Er erreicht 5 % der Fläche, d. h. fast 10 % des Gewichts, liegt aber meist bei 2 % bzw. 4 %. Über weitere allgemeine Beziehungen wurde versucht, statistisch sich einen Eindruck zu verschaffen durch Vergleich des Erzinhalts der meisten vorliegenden Proben. Notiert wurden: (Tabelle umseitig!)

Allein durch diese Statistik lässt sich ersichtlich nicht festlegen, ob — abgesehen von der Gesamterzmenge — ein Parallellaufen der Erzparagenese mit dem SiO_2-Gehalt oder auch des z. B. im Gehalt von Hämatitilmenit bzw. Titanomagnetit sich äussernden Sauerstoffpartialdruckes oder beider untereinander besteht. Jedenfalls ist eine klare Beziehung in dem immerhin spärlichen Material noch nicht zu zeigen. Sicher ist allein, dass hohe Gehalte an Hämatitilmenit und dabei besonders solche mit viel eigentlichem Hämatit sehr ausgesprochen, aber keineswegs ganz von Sulfiden gemieden werden, am wenigsten übrigens erstaunlicherweise von Pyrit, und dass hohe Sulfidmengen nur in den basischeren Gliedern vorkommen.

Bei der Einzelbesprechung der Erzmineralien werden die Paragenesen mit anderen Erzen oft noch einmal kurz angegeben. Zu behandeln sind: Magnetit, Ilmenit, Magnetkies, Kupferkies, Zinkblende, Pyrit, Pentlandit.

Magnetit, der in allen untersuchten Proben vorkommt und meist das reichlichste Erz ist, bildet Körnchen bis 1 mm Ø, in der Erzschliere bis 5 mm. Wenn der Sauerstoffgehalt des Gesteins so hoch war, dass grössere Mengen von Eisenglanz in Form

Tabelle der Erzverteilung in den untersuchten Schliffen.

	Ilmenit	Hämatit-ilmenit	Magnetit	Titano-magnetit	Magnet-kies	Kupfer-kies	Zink-blende	Pyrit	
								pr.	se.
1.	x			xx	X+	x	x	x	x
2.		x		xx		(x)		(x)	x
3.	xx		x		(x)	x	xx	?	
4.		x	xx (Ma)					x?	
5.		xx	x		x	x			x
6.	x		x (Ma)		(x)	x	x		X
7.	x (rötlich)			x	x		x		x
8.	xx	x	x		X+	x			X
9.	x	(x)		xx	x				
10.	x			xx	x	(x)			x
11.		xx	x			(x)			x
12.									

Nr. 1, 2 und 3 sind »basic charnockite» von Högahalla, Träslövsläge. Nr. 2 ist eine Erzknolle daraus.
Nr. 4, 5 und 6 sind »intermediate charnockites» von Fästningsberget, Varberg.
Nr. 7 und 8 sind grobkörnige »leucocratic charnockites» von Träslövsläge.
Nr. 9 und 10 sind »sub-acid charnockites» von Traneberg, Varberg.
Nr. 11 ist ein »felsic charnockite» von Högahalla, Träslövsläge.

Ma bezeichnet Magnetit mit starker Martitbildung
X bedeutet bei Magnetkies: zusammen mit Markasit
x+ bedeutet mit Pentlandit
xx bezeichnet Erz häufig im fraglichen Gestein.

von Hämatitilmenit sich bildeten, tritt Magnetit an Menge zurück und ist dann auch nicht mehr in der Lage, ergebliche Mengen "Ilmenitmolekül" ins Gitter einzubauen. Das spräche für die Annahme von Foslie und später Mogensen, dass ursprünglich Ti nicht als $FeTiO_3$, sondern Fe_2TiO_4 im Magnetit gelöst ist, ein Fe_2O_3-Überschuss also sinngemäss die Löslichkeit des Ti im Magnetit inhibieren müsste. Tatsächlich trifft nun aber diese Regel doch nicht ganz zu, wenn auch die Ausnahmen solche nur mit Einschränkung sind: Probe 12 enthält massenhaft Hämatitilmenit, trotzdem der Magnetit vereinzelt Ilmenitlamellen führt, die Erzschliere massenhaft Magnetit mit vereinzelten Ilmenitlamellen, trotzdem im ebenfalls massenhaften Ilmenit etwa 25 % Hämatitlamellen stecken. Immerhin ist auch hier der Ilmenitanteil im "Titanomagnetit" nicht hoch und ausserdem auf die äusseren Teile des Kornes beschränkt, gerade diejenigen, die mit den äusseren Fe_2O_3 -armen Teilen der Hämatitilmenite gleichalterig sein mögen.

Wo aber durch O-Gehalte keine Komplikationen eintreten, ist der Titanomagnetit typisch, aber kein solcher mit besonders hohem $FeTiO_3$ Anteil (Abb. 1), obwohl massenhaft freier Ilmenit gleichzeitig vorhanden ist. Die Ilmenitlamellen sind, wie das bei sonstigen magmatischen Gesteinen (aber eigentlich nur bei basischeren!) häufig ist, gesäumt mit Spinellkörperchen. Auch selbständige, dann aber mehr strichförmige Spinellentmischung (allerdings sehr fein) ist überall zu sehen. Es gibt Fälle, wo der Spinell einen ziemlich nennenswerten Anteil ausmacht und durch seine (100) Lamellen eine Art Pseudospaltbarkeit im Magnetit bedingt.

Die Entstehungsgeschichte des Magnetits wird kompliziert weiter dadurch, dass Magnetit im späten Teil der Gesteinsverfestigung wenigstens in einigen Gesteinen

[illegible]

[illegible]

[illegible]

[illegible]

nur mit dem Fe_2O_3-freien jüngsten Ilmenitanteil. Mit anderen Worten: In frühen Stadien der Gesteinsbildung ist der Fe_2O_3-Anteil hoch; er nimmt zu Gunsten des FeO-Anteils kontinuierlich ab. vergl. Abb. 2, 3, 4,). Das äussert sich sogar in den Entmischungskörpern im Hypersthen.

In den letzten ist "Ilmenit" besonders früh, zunächst in gelöster Form dem Magma entzogen und festgelegt worden. Wann die Entmischung einsetzte, ist an sich belanglos (und nicht feststellbar!), jedenfalls haben diese Körper die chemischen Verhältnisse im Frühstadium konserviert. Die manchmal recht grossen, eigentlich nie unter ein bestimmtes Mass heruntergehenden Körper (Abb. 5) bestehen nun nicht aus Ilmenit, sondern einem eigentlich überall ganz grob entmischten Hämatitilmenit mit 50 und sogar mehr % Hämatitanteil!

Es ist selten, dass über die Oxydationsstufe des Eisens und ihre Änderung im Verlauf der Erstarrung Angaben zu machen sind — hier sind sie augenfällig. Es ist dabei an zwei Beobachtungen zu erinnern: a) Dass *Goranson* aus einer Schmelze granitischer Zusammensetzung als früheste Ausscheidung (lange bevor andere feste Phasen erscheinen) Kristalle von Eisenglanz feststellt, die im normal erstarrten Gestein dann wieder völlig verschwinden. Es ist wohl anzunehmen, dass es sich dabei in Wahrheit um Fe_2O_3-$FeTiO_3$-Mischkristalle gehandelt hat. Unter diesem Gesichtspunkt gewinnen auch die vom Verf. erstmalig, später mehrfach von anderen beobachteten Umkrustungen sehr Fe_2O_3-reicher Hämatitilmenitkerne, die rundlich resorbiert und dann mit Fe_2O_3-armer Ilmenitkruste weitergewachsen sind, eine besondere Bedeutung. b) Dass im Verlauf jeder Magmenerstarrung die SiO_2-führenden Mineralien allgemein saurer, d. h. gleichzeitig O-reicher werden. Damit wird verständlich, dass zuerst vorliegende O-reiche Verbindungen zu Gunsten der Silikate abgebaut werden. Das gilt natürlich nur als grobe Regel.

3.) Die grösseren Ilmenitpartien pflegen xenomorph bis teilidiomorph zu sein, während Magnetit, von Sonderfällen abgesehen, ganz xenomorph ist. Demgegenüber sind oft ziemlich späte, offenbar in Zwickeln der Restkristallisationen ausgeschiedene und demgemäss nach dem Gesagten Fe_2O_3-freie kleine Körner gut idiomorph. Sie sind es dann auch, die teilweise oder restlos in "Leukoxen" (Abb. 6) übergeführt sind. Daran ist nicht nur ihre geringe Grösse schuld, da ja auch dünne lappige Fortsätze der älteren Ilmenitgeneration im selben Gestein intakt sind; sondern ich glaube, dass die Lage in den Spätkristallisationszwickeln, wo auch der Nachhall des Erstarrungs vorganges, die hier an sich sehr geringe hydrothermale Autometamorphose sich auswirkte, der Anlass war.

4.) Die auffallend verschiedene Färbung der Ilmenite muss auf den Gesamtchemismus des Gesteins irgendwie zurückzuführen sein. Verf. hat mehrfach darauf aufmerksam gemacht, dass abweichende Färbung (mehr grau als braun in Oel) und Reflexionsvermögen (erheblich schwächer in Oel) mit Mg-Gehalt, d.h. also Anteil an Geikielithkomponente zusammenhängen. Es gibt auch Fälle, wo der rötliche Ton reiner $FeTiO_3$-Ilmenite stark überbetont erscheint. Bei der grossen Zahl von Möglichkeiten, die sich für Vertretungen im Ilmenit-Eisenglanzgitter bieten, ist ohne Analyse hier eine Erklärung noch unmöglich. *Beide* eben dargestellten Möglichkeiten sind in Gesteinen von Varberg realisiert, konnten aber nicht weiter verfolgt werden.

Noch eine mir bisher völlig neue Besonderheit an Ilmeniten muss erwähnt werden, die oft der Ilmenit der besonders granatreichen Varietät zeigt. Während alle, aber auch alle von mir untersuchten und auch im Schrifttum erwähnten entmischten Hämatitilmenite zentral, also in den ältesten Teilen, die höchsten Hämatitgehalte zeigen, allenfalls einmal überhaupt keinen Zonenbau haben, ist hier an Ilmeniten, die sich zunächst ganz normal verhalten, aussen ein besonders eisenglanzreicher Saum entwickelt, der an den idiomorphen Kristallen relativ dick auf den Pyramiden und Rhomboedern, dünn oder sehr dünn der Basis aufsitzt (Abb. 7). — Die Erklärung ist bei dem sonst, wie geschildert, ganz typischen Gang der Sauerstoffabnahme in den Eisenerzen recht schwierig. Es muss hier eine irgendwie geartete Rekurrenz vorliegen. Ob sie nur chemischer oder thermischer Natur war, oder ob vielleicht die Teilresorption des Granats in diesem Gestein beteiligt ist, wage ich nicht zu entscheiden.

Andere oxydische Erzmineralien, abgesehen natürlich von recenter Brauneisenverwitterung einiger Sulfide in den Oberflächenkrusten der Gesteine fehlen; nur winzige Mengen von *Rutil* sind neben Eisenglanz gelegentlich aus $FeTiO_3$ entstanden.

Sulfide. Von Sulfiden ist *Pyrit* weitaus überwiegend. Er ist in in mehreren genetisch sicher verschiedenen Generationen vorhanden, die manchmal leicht, manchmal aber auch garnicht an ihren Formen unterscheidbar sind.

1.) Sehr alte, meist sehr kleine idiomorphe Einschlüsse in den primären Silikatmineralien. Sie sind allem Anschein nach etwa gleichalterig und isogenetisch mit den ,,Magnetkiesströpfchen''.

2.) Hypogen aus Magnetkies entstanden in manchmal sehr typischen Pseudomorphosen, oft mit Relikten von jenen. Es bilden sich geschlossene körnige Krusten um Magnetkies, der mehr und mehr weggelaugt wird. Oft liegen hohle Zellen von Pyrit vor.

Dieser Pyrit ist etwa gleichalt mit den jüngsten Teilen des Magnetits. Es scheint auch hier bereits etwas Markasit vorzukommen.

3.) Supergen aus Magnetkies entstanden, oft mit Markasit zusammen. Ebenfalls in Pseudomorphosen, die aber — wenigstens im typischen Fall — anders aussehen als in 2.

4.) Infiltrationsartig auf Klüften, wohl ebenfalls letzen Endes auf Magnetkies zurückgehend und aus einer zirkulierenden Sulfidlösung irgendwie gefällt (Abb. 10).

Pyrrhotin ist ursprünglich das häufigste Sulfid, das aber vielfach schon früh, wenigstens teilweise schon in Spätstadien magmatischer Tätigkeit, zur Hauptsache unter Einwirkung des Grundwassers bzw. der Bergfeuchtigkeit fast völlig in Pyrit, Markasit, ganz selten auch das ,,Zwischenprodukt" zersetzt ist (Abb. 9).

1.) Oft erhalten, da frühzeitig gegen alle Einflüsse gepanzert, sind die ,,Kügelchen'', Schmelztropfen aus der Frühzeit der Silikaterstarrung. Sie sind an sich spärlich und längst nicht in allen Proben nachgewiesen, allerdings auch leicht zu übersehen. In sehr seltenen Fällen sind sie als komplex, bestehend aus Magnetkies, wenig Kupferkies und Pentlandit erkennbar. Einmal ist auch Zinkblende als Begleiter nachgewiesen.

2.) Die Hauptmasse des Magnetkieses liegt (bzw. lag!) in Zwickelfüllungen älterer Silikate, besonders aber neben Magnetithaufen (Abb. 8), diesen gegenüber sogar oft etwas idiomorph, vor. Der neuentstandene Pyrit und oft Markasit bildete zunächst eine kompakte und relativ grobe Aussenkruste, die meist erhalten blieb, während die Kernteile oft ganz oder teilweise noch als Magnetkies oder auch schon als sehr feinkörniger Pyrit weggelöst sind. Gelegentlich bilden sich die bekannten netz- oder skelettförmigen Pseudomorphosen (Abb. 7).

Noch jüngerer Magnetkies findet sich auf Sprüngen in Ilmenit und Magnetit und könnte für einen Teil, aber nur einen solchen, des infiltrationsartig auftretenden Pyrits verantwortlich gemacht werden.

Kupferkies, der sonst in magmatischen Gesteinen so treue Begleiter fast eines jeden Magnetkieskorns, ist hier zwar auch recht verbreitet, aber insgesamt auffallend selten. Er liegt meist im oder neben Magnetkies, ist xenomorph und ohne jede Auffälligkeit.

Sehr merkwürdig ist der ziemlich stetige und relativ sehr hohe Gehalt an *Zinkblende.* Fast immer neben Magnetkies führt sie diesen oder Kupferkies oder beide als Entmischungskörper. Natürlich ist die absolute Menge klein, aber die Verbreitung des in orthomagmatischen Gesteinen so seltenen Minerals doch ganz auffällig. Während man sonst den Zinkgehalt magmatischer Gesteine sicher mit Recht im Magnetit oder Spinell sucht, haben hier Bedingungen geherrscht, die gewissermassen die Chalkophilie des Zinks begünstigten, wahrscheinlich einfach hoher Partialdruck an Schwefel (Abb. 7, 8).

Als letztes Sulfid wäre zu nennen *Pentlandit*, der als solcher oder übergeführt in Bravoit in einigen der erzreichsten Gesteine immer neben Magnetkies vorkommt. Er ist, besonders gemessen am Zinkblende-, aber auch am Magnetkiesgehalt ausgesprochen selten!

Auf andere Erze wurde vergeblich geachtet.

Bemerkenswert vom erzmikroskopisch-technischen Standpunkt ist noch, dass ausgezeichnet die „Leukoxenumbildung" des Ilmenit zu beobachten ist (Abb. 6), und dass trotz ihrer Kleinheit die Körnchen als Titanit erkannt werden können. Weiter, dass besonders in Oelimmersion die Neubildung des Rutilskeletts in zersetztem Biotit sehr gut verfolgt werden kann (Abb. 11). Dabei ist besonders bemerkenswert, dass die Rutilnadeln paketweise immer nur in bestimmten Basisniveaus des Biotits auftreten, während dickere Platten im selben Glimmer völlig frei davon sind.

Zusammenfassend ist nur zu sagen, dass auch der Erzinhalt entschieden die Sonderstellung charnockitischer Gesteine zu betonen scheint, dass er auf eine langdauernde und relativ hochtemperierte Erstarrung mit komplizierter Geschichte deutet und schliesslich eine Verarmung des Magmas, mindestens des Erzinhalts an Sauerstoff erkennen lässt. Auffallend ist der relativ hohe Gehalt an Zinkblende.

APPENDIX II

On the distribution of the ferrides in the charnockite series and rocks of the surrounding formation

By Sture Landergren

Introduction

In connection with the petrological investigation of the charnockite series and associated rocks by professor Percy Quensel the present author has made a determination of the content of the ferride series (viz. Ti, V, Cr, Mn, Fe, Co, and Ni) on the proposal of Quensel who has put his research material at my disposal. This material has previously been chemically analysed of the content of the major constituents.

The determination of vanadium, chromium, (manganese), cobalt, and nickel has been made spectrochemically by means of methods familiar to any geochemist (cf. Landergren, 1948). The figures for titanium and iron have been recalculated from the chemical analyses. The content of manganese has been spectrochemically controlled, and the chemical and spectrochemical analyses are in reasonable agreement.

To illustrate the mutual relationship between the ferrides and that between the ferrides and the significant major constituents (including FeO and Fe_2O_3) the correlation coefficients (r-values) have been calculated for some significant pairs of elements.

The distribution of the ferrides

In Table 1 the content — in parts per million — of the ferrides in the samples analysed are presented. The number of the rock samples, the rock names, and their localities are in correspondence with Quensel's description. (Table 1.)

From Table 1 is seen that the concentration of the ferrides is antibatic with that of SiO_2 the content of which is added to the table in order to facilitate the discussion. The three basic end members of the rocks analysed, viz. the meta gabbro (no.3) and the amphibolites (nos. 4 and 5) show a ferride content of the same order of magnitude as that significant for igneous rocks in general of a similar basicity. These rocks are, namely, the natural home for the ferrides to become enriched in comparison with the average of the upper lithosphere.

The salic end members of the rock series — the aplitic granite (no. 16) and the gneiss (no. 17) — show a very low content of those ferrides significant for the basic rocks. This trend is also in full agreement with previous investigations of the distribution of the ferrides in salic rocks (Landergren, 1948).

In the charnockite series the content of the most significant members of the ferride group, vanadium, cobalt, and nickel, seems to be rather completely dependent on their basicity. The two basic charnockites (nos. 1 and 2) have a ferride content very similar to that of the basic rocks mentioned (nos. 3—5). This points to a genetic relationship between the rocks discussed in agreement with Quensel's conclusion arrived at from a petrological point of view. In this connection should be mentioned that the content of chromium in one of the basic charnockites (no. 2) is in bad ag-

T

The distribution of the ferrides in the charnockite se

No.			SiO_2 (weight-
1	Charnockite, basic	Högahalla, Träslövsläge	44.60
2	Charnockite, basic	Lassabacka	45.00
3	Meta gabbro	Ullared	45.56
4	Amphibolite	Bankahalla, Träslövsläge	46.52
5	Amphibolite, garnetiferous	Getterön	46.28
8	Charnockite, intermediate	Apelviken	53.96
9	Charnockite, intermediate	Fästningsberget, Varberg	60.12
10	Charnockite, leucocratic	Harbour of Träslövsläge	62.04
11	Charnockite, silicified	Björka, Trönninge	51.60
12	Charnockite, subacid	Traneberg, Varberg	61.86
13	Charnockite, felsic	Högahalla, Träslövsläge	68.12
14	Charnockite, felsic	Himle	72.32
15	Hybrid rock	Bankahalla, Träslövsläge	68.16
16	Granite, aplitic	Högahalla, Träslövsläge	73.72
17	Gneiss of the surrounding Formation (»Järngneis»)	Bankahalla, Träslövsläge	70.92

greement with the other basic rocks. This deviation, however, is insignificant if bearing in mind the often occurring irregularity in the distribution of this element in the igneous rocks.

Of interest is the ferride content in the silicified charnockite (no. 11). According to Quensel the increasing content of SiO_2 in this charnockite can be connected with secondary pneumatolytic processes. The distribution of the ferrides in the rock is evidently similar to that of the basic charnockites. The secondary processes, including increase in the content of SiO_2 have obviously had but little influence on the primary distribution of the ferrides in the charnockite mentioned.

The decreasing content of ferrides in the salic members of the charnockite series corresponds to the increasing content of SiO_2 and may be regarded as quite normal for igneous rocks in general, independent of any hypothesis of their origin.

The ratio Ni: Co shows no remarkable deviation from that of igneous rocks in general. In the basic rocks the ratio is >1. Increasing acidity of rocks tends towards a ratio ≤ 1, viz. a normal feature in the distribution of these two elements in the igneous rocks.

The correlation between major constituents and ferrides

As earlier mentioned the content of the ferrides is antibatic with the content of SiO_2 or symbatic with the basicity of the rocks. In order to find out the magnitude of the relationship of some significant pairs of elements the correlation coefficients have been calculated based on the analytical material at my disposal. The magnitude of the correlation coefficient — called the r-value — can vary between $+1$ (proportionality) and -1 (inverse proportionality). Thus the magnitude of r can be regarded as a quantitative expression for a relationship between two quantites.

In Table 2 the r-values of some significant pairs of elements are presented.

As seen from the table the r-values are fairly high in most cases observed and nd rocks of the surrounding formation (in p. p. m.).

Ti	V	Cr	Mn	Fe	Co	Ni	Ni : Co
30 700	200	200	1 400	130 600	30	200	6.7
14 400	480	40	2 800	112 000	40	60	1.5
2 200	150	100	1 000	54 500	30	250	8.3
9 000	280	200	3 200	106 500	30	90	3.0
14 400	440	300	1 800	122 900	40	110	2.8
14 700	60	10	2 400	67 200	10	5	<1
5 700	<10	<10	900	52 900	<10	5	1 (appr.)
3 600	30	40	1 000	23 200	<10	20	>2
6 000	250	10	1 300	77 400	20	110	5.5
4 800	140	10	1 000	40 000	10	10	1
1 800	60	10	500	23 500	<10	6	—
1 000	10	<10	300	13 900	<10	5	—
1 800	30	<10	900	24 300	≤ 10	5	—
1 200	20	<10	200	12 900	<10	6	—
1 900	20	≤ 10	800	20 900	<10	6	—

Table 2.

Correlation coefficients for some significant elements.

	SiO_2	MgO	Fe_2O_3	FeO	V	Co	Ni
SiO_2	—	−0.92	−0.65	−0.81	—	—	—
MgO	−0.92	—	—	+0.76	—	+0.91	+0.83
Fe_2O_3	−0.65	—	—	—	+0.75	—	+0.48
FeO	−0.81	+0.76	—	—	+0.71	+0.80	+0.67
V	—	—	+0.75	+0.71	—	—	—
Co	—	+0.91	—	+0.80	—	—	—
Ni.............	—	+0.83	+0.48	+0.67	—	—	—

evidently significant. Thus, there is all but inverse proportionality between SiO_2 and MgO ($r = -0.92$). A rather high negative correlation also exists between the pairs of major constituents SiO_2–FeO, SiO_2–Fe_2O_3, and MgO–FeO. These high r-values correspond to those between MgO, FeO, and Fe_2O_3 on the one hand and V, Co, and Ni on the other, as seen from Table 2. Some significant details are worth mentioning. The r-values of Ni–MgO, Ni–FeO, and Ni–Fe_2O_3 decrease successively (+0.83, +0.67, and +0.48 respectively) depending on the ionic size and charge in six-coordination for the ions Ni^{2+} (ionic radius 0.78 kX), Mg^{2+} (i.r. 0.78 kX), Fe^{2+} (i.r. 0.83 kX), and Fe^{3+} (i.r. 0.67 kX). These r-values are in excellent agreement with the distribution principle for nickel showing that this element preferebly enters in Mg-mineral structures due to the similarity in ionic size, as asserted by V. M. Goldschmidt (1937).

Sandell and Goldich (1943) have pointed out that cobalt also preferably enters Mg-mineral structures and not Fe-mineral structures as supposed by Goldschmidt, since the i.r. for Co^{2+} is equal to that of Fe^{2+} (0.83). In this case the r-value for

Co–MgO is +0.91 and that for Co–FeO +0.80 in agreement with the investigation by Sandell and Goldich.

The correlation between vanadium and iron is interesting. The *r*-value for $V–Fe_2O_3$ is +0.75 and that for V FeO +0.71. One could expect that the correlation $V^{3+}–Fe^{3+}$ should be much stronger than that for $V^{3+}–Fe^{2+}$ since the ionic size and charge for the former ions are similar. The similar *r*-values may be explained so that vanadium enters mineral structures where both tri- and bivalent iron ions occur (viz. magnetite).

The rather strong correlation between the elements mentioned above indicate that the mineral facies represented in the rock samples investigated have been formed under such endogenic conditions that some kind of 'equilibrium' with respect to the ferrides has been reached and a crystal chemical distribution principle can be applied. It is also plausible to believe that there exists a genetic relationship between the rock members studied for the same reason. Lack on suitable material for comparison, however, makes an unambiguous conclusion impossible at present. On the other hand: if a genetic relationship between the rocks is likely from a petrological point of view nothing in the distribution of the elements discussed is in contradiction to such a conclusion.

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Tryckt den 7 september 1951

Uppsala 1951. Almqvist & Wiksells Boktryckeri AB

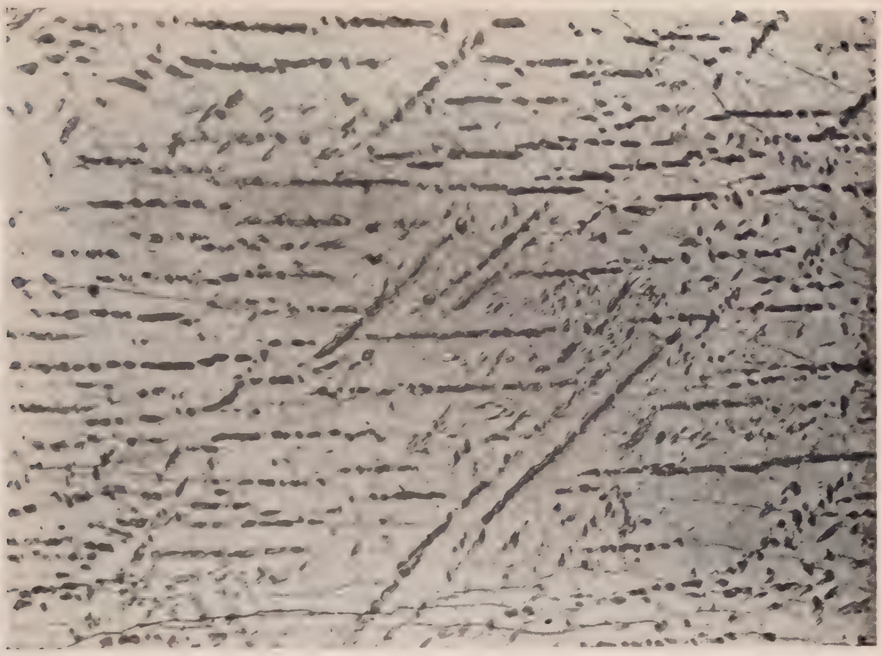


Fig. 1. Antiperthite with orientated lamellae of plagioclase. × 45. Sub-acid charnockite, Traneberg, Varberg.

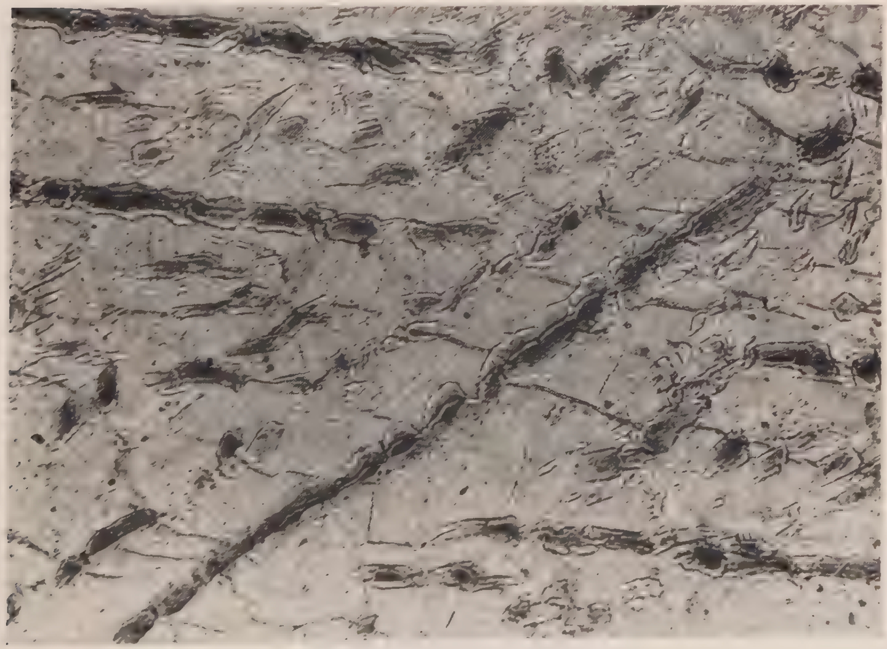


Fig. 2. Lower right corner of Fig. 1 enlarged. × 150.

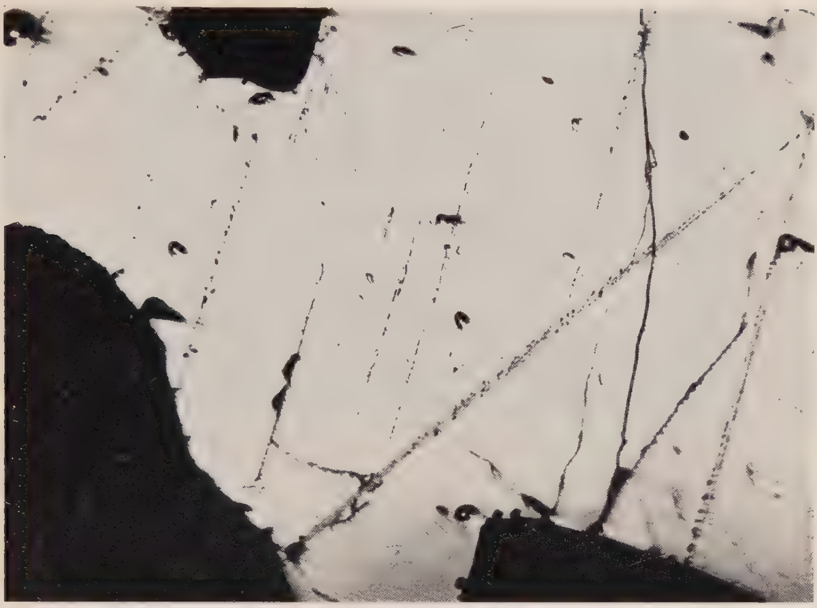


Fig. 1. Titanomagnetit in »intermediate charnockite». × 250. Oelimmersion. Fästningsberget, Varberg. *Magnetit* mit wenigen groben Ilmenitlamellen, die von Spinellkörnchen gesäumt sind. Wenig Pyrit an einem Sprung.

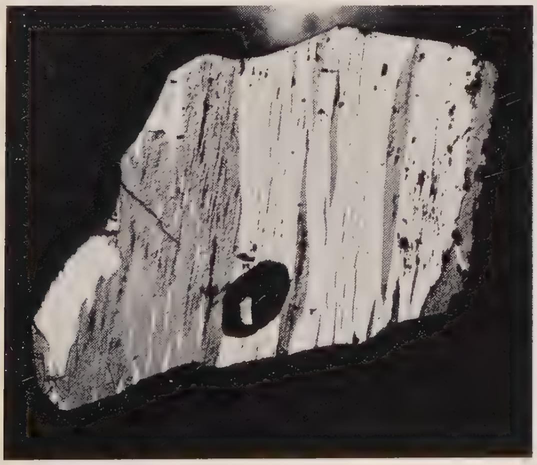


Fig. 2. *Hämatitilmenit* im grobkörnigen leukokraten Charnockit. × 250. Oelimmersion. Träslövsläge. Hämatit und Ilmenit; Hämatit überwiegt etwas. Zwei Entmischungsgenerationen sehr verschiedener Grösse. Ilmenit im Verwitterungsbeginn. Randlich ist bei dieser sehr frühen Bildung keine Abnahme des Hämatitanteils erkennbar.

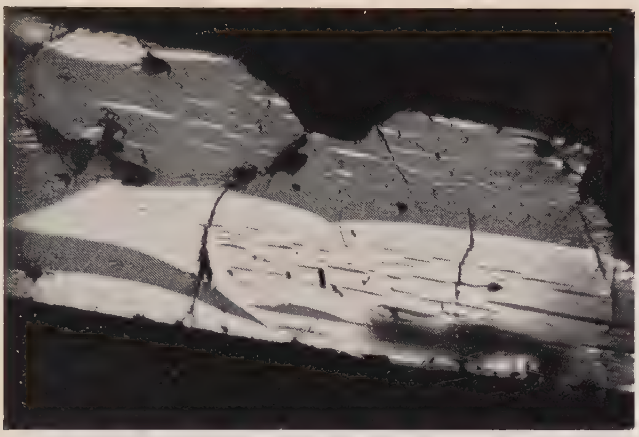


Fig. 1. *Hämatitilmenit* vom selben Gestein als oben (Pl. II:2). × 300. Oelimmersion. Hämatit und Ilmenit etwa gleichviel. Einzelkristall mit beidseitigem (0001). Dieses Bild zeigen bei entsprechend stärkerer Vergrösserung die Entmischungskörper im Hypersthen.

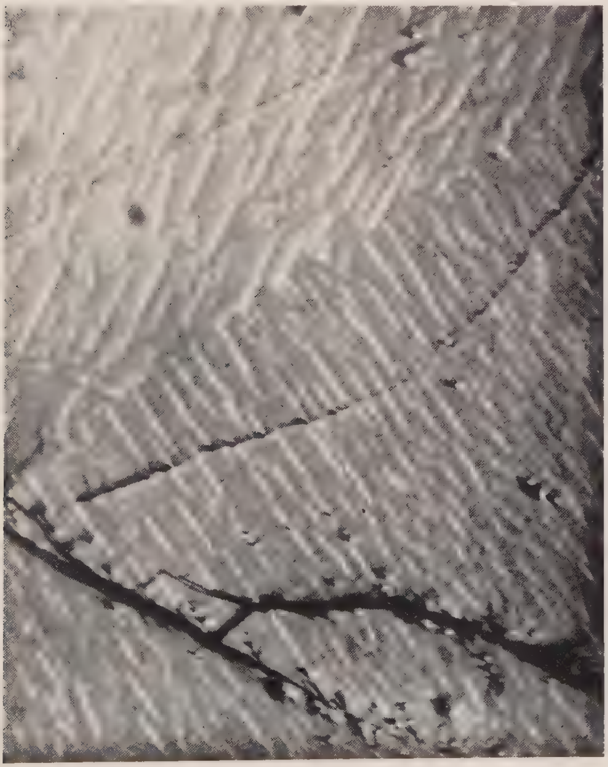


Fig. 2. *Hämatitilmenit* im »basic charnockite». × 600. Oelimmersion. Träslövsläge. Ilmenit herrscht stark vor. Bequem sichtbar nur die grobe Entmischungsgeneration.

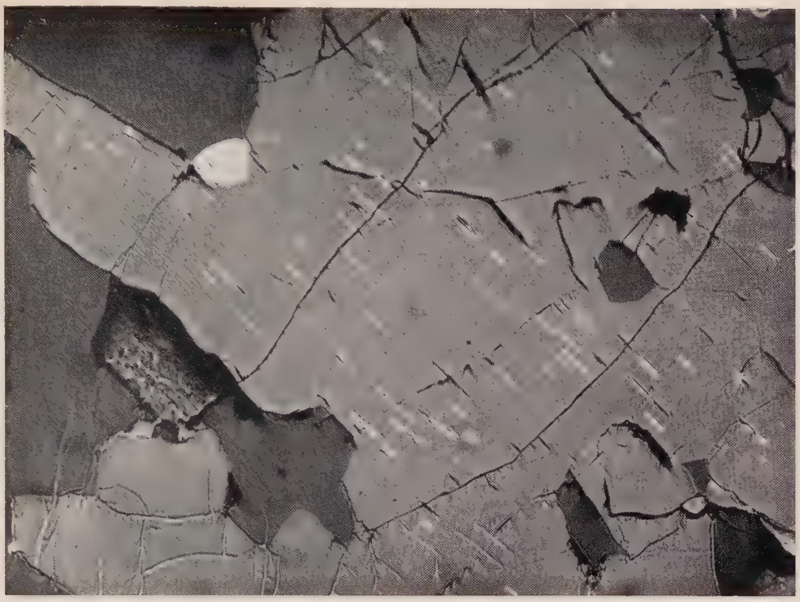


Fig. 1. Ilmenit (korrekter Hämatitilmenit) als Entmischungskörper im Hypersthen. Wenig Magnetkies. × 100. »Basic charnockite», Träslövsläge.

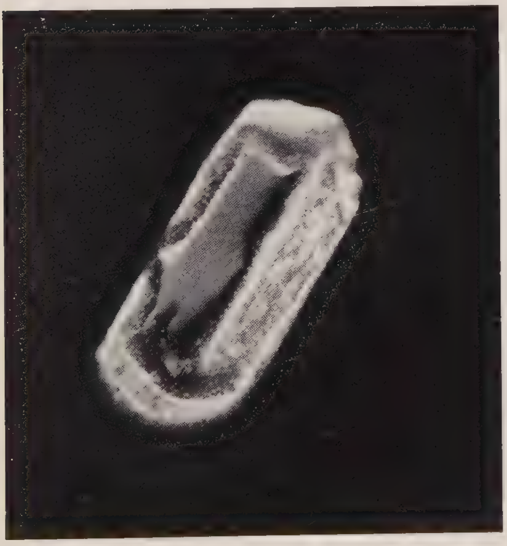


Fig. 2. *Ilmenit* als späte aber idiomorphe Bildung, sehr weitgehend in Leukoxen, hier wirklich Titanit, verwandelt. × 750. Oelimmersion. »Intermediate charnockite», Fästningsberget, Varberg.

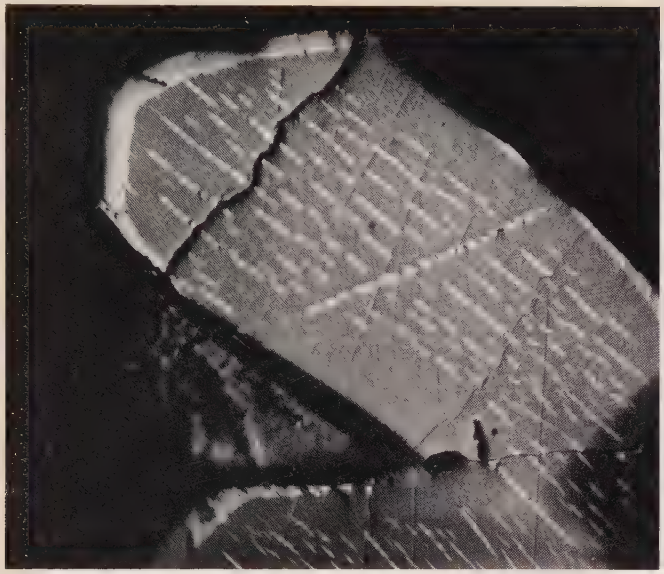


Fig. 1. *Ilmenit*, zentral ein normaler Hämatitilmenit mit randlich abnehmendem Hämatitgehalt. Ganz aussen folgt als Rekurrenzbildung eine ganz hämatitreiche Partie. × 500. Oelimmersion. »Sub-acid charnockite», Traneberg, Varberg.

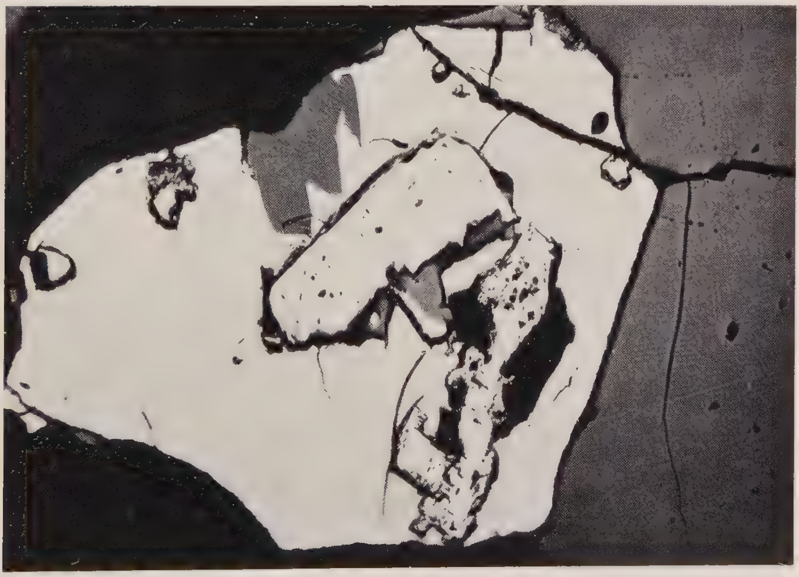


Fig. 2. Typischer grösserer Sulfidzwickel neben Magnetit (grau) und Silikaten (schwarz). Hauptgemengteil (weiss) ist hier frischer *Magnetkies*, daneben wenig und kaum unterscheidbar etwas *Kupferkies* (bes. zwischen Zinkblende und Pyrit). Weiss mit starkem Relief und Polierlöchern ist *Pyrit*. Dunkelgrau mit wenigen Kupferkieskörperchen ist *Zinkblende*. × 250. »Intermediate charnockite», Fästningsberget, Varberg.

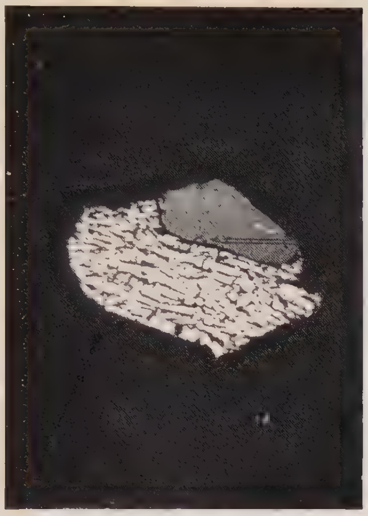


Fig. 1. *Magnetkies*, restlos in *Pyrit* umgewandelt. Dabei entwickelt sich die Spaltbarkeit des Magnetkies zu Löchern. Dunkelgrau mit vielen Kupferkieskörpern ist *Zinkblende*. × 220. Oelimmersion »Basic charnockite», Träslövsläge.

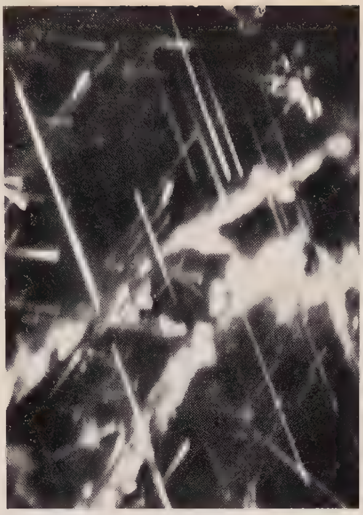


Fig. 2. Rutilnadeln eingelagert im etwa // (001) geschnittenen Biotit. × 500. Oelimmersion. »Sub-acid charnockite», Traneberg, Varberg.

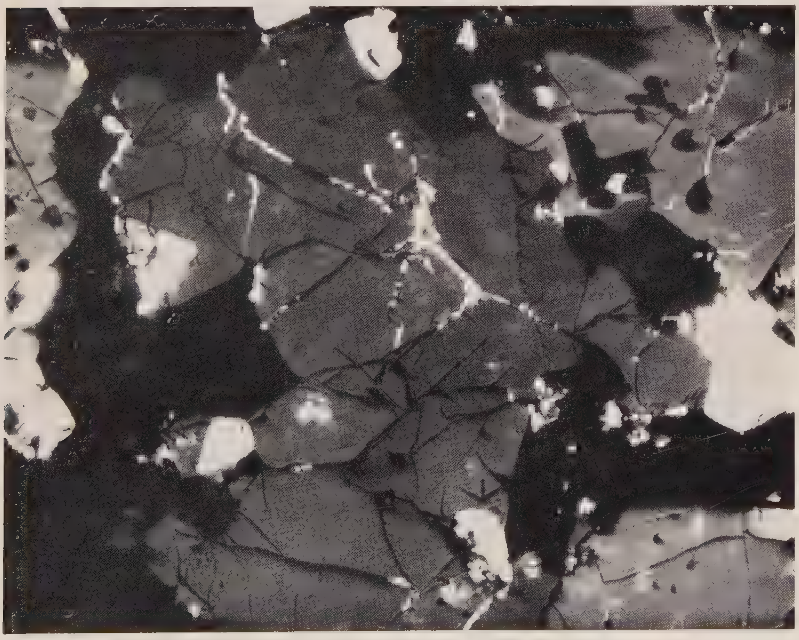
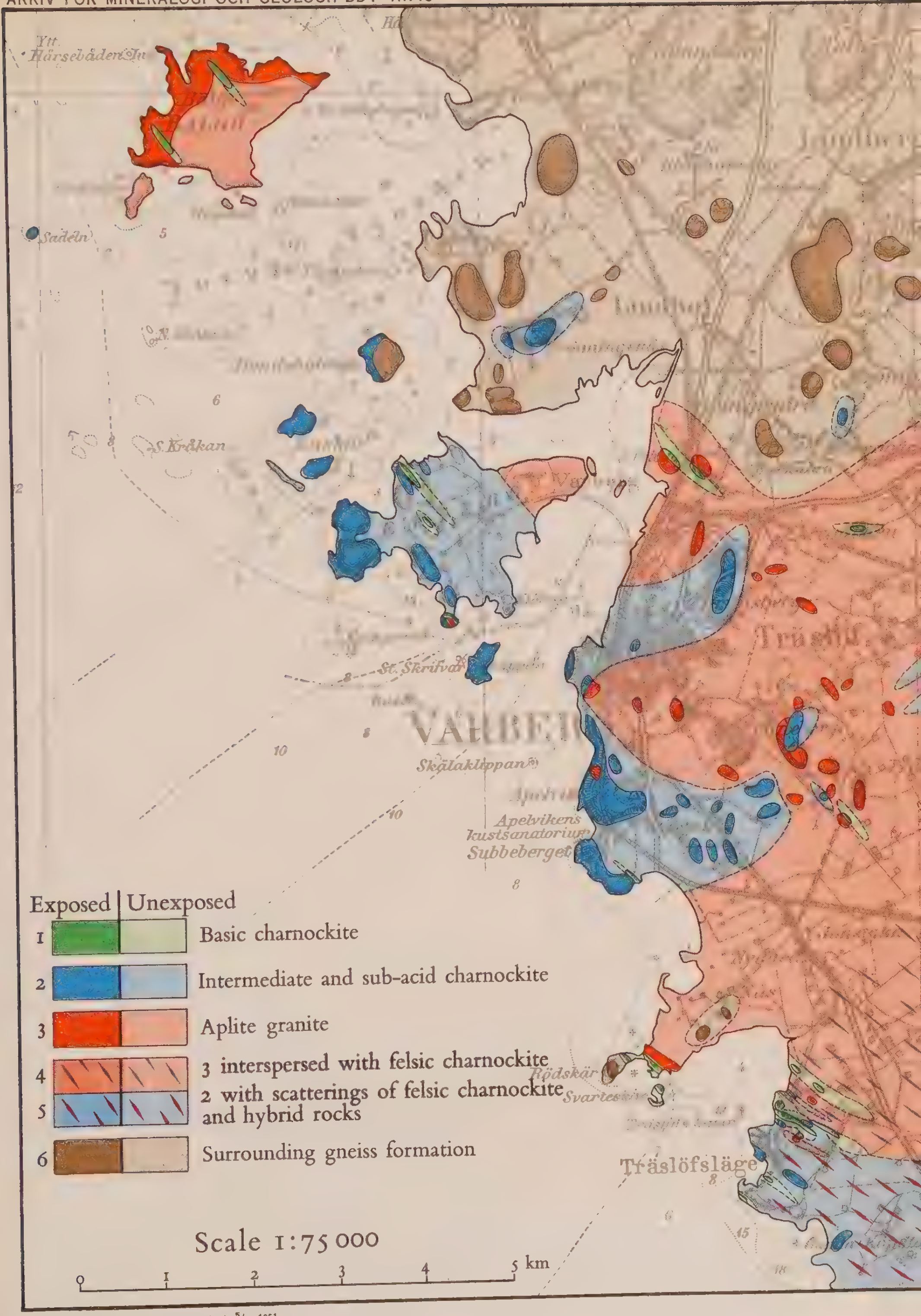


Fig. 3. Pseudomorphosen von *Pyrit* nach *Magnetkies*, hier in geschlossenen Massen. Wohl von ihnen aus ist Pyrit auch an Korngrenzen und Spaltrissen ins Nebengestein infiltriert. × 100. Oelimmersion. »Basic cnarnockite», Träslövsläge, Varberg.

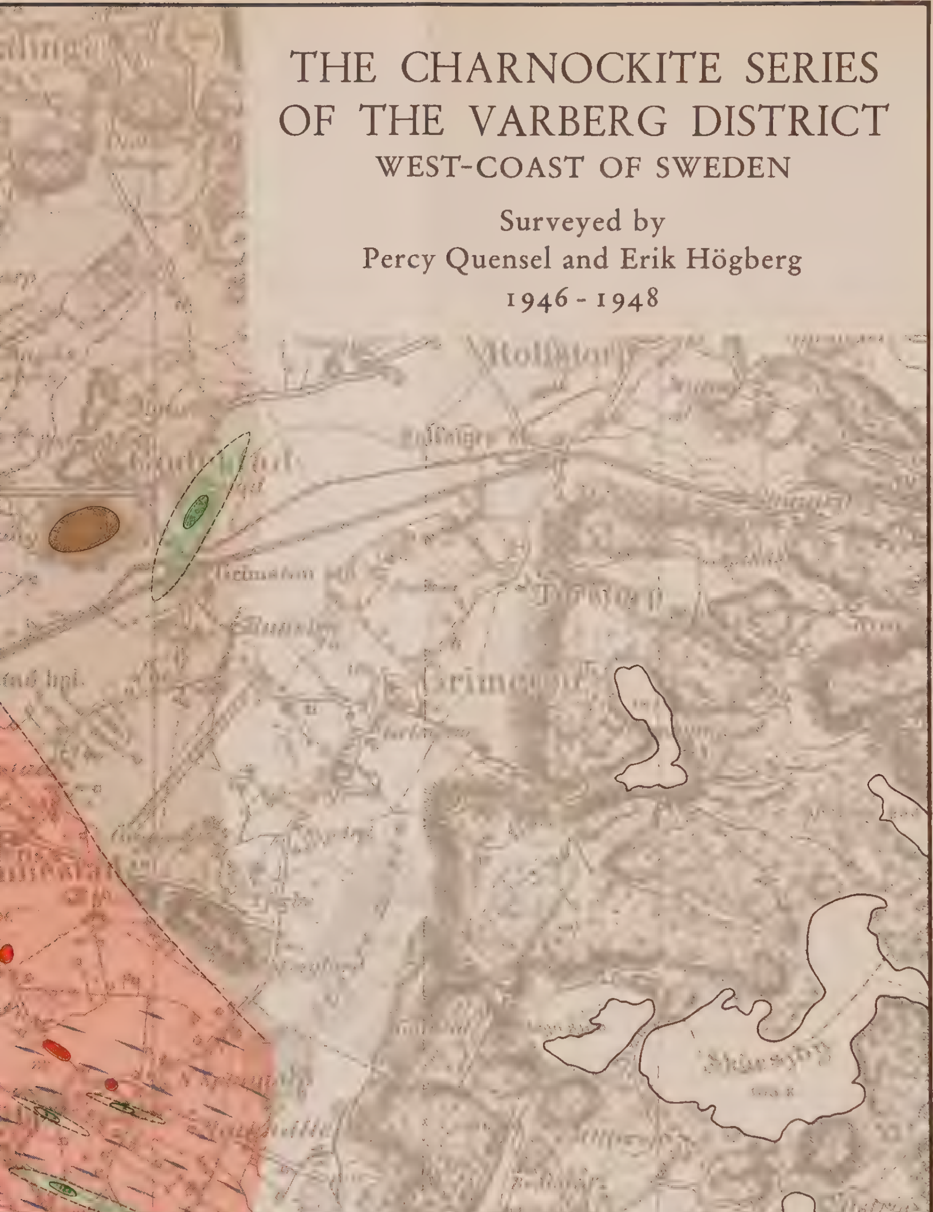

Ytt. Härsebåden
Sadeln
S. Kråkan
St. Skrifvan
VARBERG
Skalakläppan
Apelvikens kustsanatorium
Subbeberget
Rödskär
Svarteskär
Träslöfsläge
Träslöf
Exposed
Unexposed
1 Basic charnockite
2 Intermediate and sub-acid charnockite
3 Aplite granite
4 3 interspersed with felsic charnockite
5 2 with scatterings of felsic charnockite and hybrid rocks
6 Surrounding gneiss formation
Scale 1:75 000
0 1 2 3 4 5 km

För publicering godkänd i Rikets allmänna kartverk 5/6 1951

THE CHARNOCKITE SERIES OF THE VARBERG DISTRICT

WEST-COAST OF SWEDEN

Surveyed by
Percy Quensel and Erik Högberg
1946 - 1948



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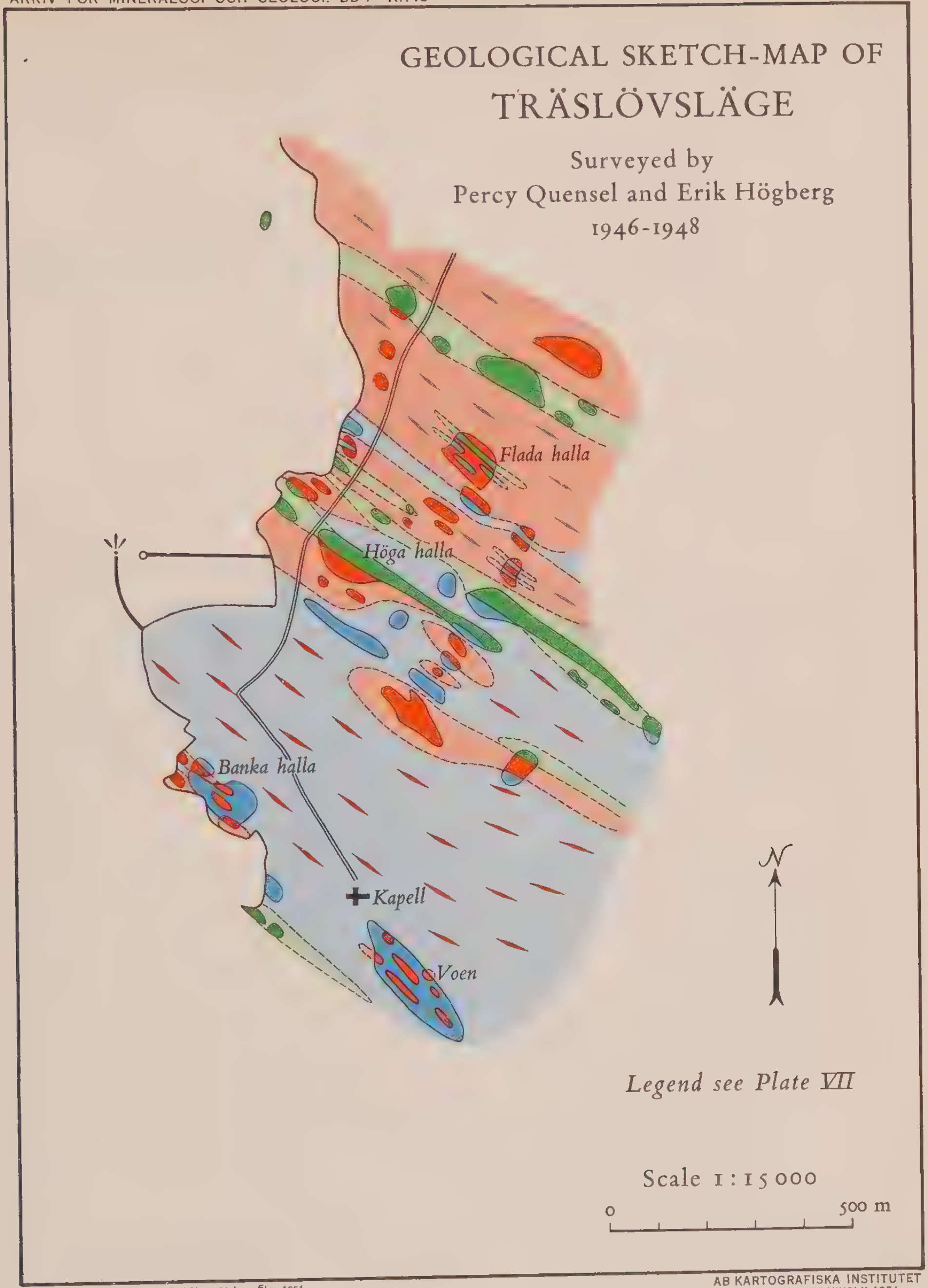

GEOLOGICAL SKETCH-MAP OF TRÄSLÖVSLÄGE

Surveyed by
Percy Quensel and Erik Högberg
1946-1948

Legend see Plate VII

Av Kartverkskommissionen godkänd för spridning 6/6 1951
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ARKIV FÖR MINERALOGI OCH GEOLOGI Band 1 nr 11

Communicated 25 April 1951 by Percy Quensel and Harry von Eckermann

Manganiferous hoernesite and manganese-hoernesite from Långban, Sweden

By O. Gabrielson

With chemical analyses by R. Blix

With 1 figure in the text

The mineral investigated occurs as a rarity in small fissures in the Långban mine, Värmland, Sweden. Chemically it is a hoernesite [$Mg_3(AsO_4)_2 \cdot 8\,H_2O$] with magnesium replaced by manganese in various proportions. When the percentage of manganese is greater than the percentage of magnesium, the name of manganese-hoernesite is proposed. This choice of name has the advantage of not burdening the mineralogical nomenclature with a new name. When the percentage of magnesium predominates, the mineral is called manganiferous hoernesite.
Originally the late professor G. Aminoff had intended to start an investigation of this mineral but only the chemical analysis of the manganese-hoernesite had been performed before his death.

Morphological crystallography. The manganese-hoernesite and the manganiferous hoernesite form minute needle-like crystals or small, elongated crystals, which are flattened along (010) surface and resemble crystals of gypsum. The crystals are concentrated in radiating aggregates, often star-formed. The maximum diameter of these "stars" is 1 cm. The crystals show an imperfect habit and only the pinacoid surface (010) is perfectly developed. Imperfect cleavage planes occur parallel to (100), (201) and (201). The flattened crystals are sometimes terminated by surfaces, developed along the cleavage-planes (201) and (201). In the microscope the angle between (201) and (100) and between (201) and (100) was found to be 39° and 54° respectively. Zambonini (1919) found the same angles to be 39° and 55° in hoernesite from Campania in Italy. The planes (201) and $(\bar{2}01)$ have been indexed as (101) and $(\bar{1}01)$ by him.

Physical properties. Perfect pinacoidal cleavage along (010). Imperfect cleavage along (100), (201) and (201). White to colorless. Streak white. Thin plates are transparent. Luster on cleavage surfaces silky. Hardness 1. Spec. gravity was calculated to be 2.76 from the volume of the unit cell. With heavy liquids the value 2.64 was obtained. Probably the low value depends upon inclusions of air in the crystal aggregates.

Structural data. The X-ray diffraction data of manganese hoernesite (powder photographs, Fe-radiation with Mn-filter) are given in table 1.

Table 1

X-ray powder diffraction data for manganese-hoernesite, Långban, Sweden (RMA 251065), (Fe-radiation with Mn-filter).

No.	*h k l*	$\sin^2 \theta$ (obs)	$\sin^2 \theta$ (calc.)	I	d
1	1 2 0	0.0140	0.0142	8	8.19
2	0 4 0	0.0191	0.0190	10	7.01
3	1 1 1	0.0441	0.0440	1	4.61
4	1 6 0	0.0521	0.0522	2	4.24
5	2 4 0	0.0567	0.0566	2	4.07
6	3 2 0	0.0889	0.0894	6	3.25
7	3 1 1	0.0984	0.0971	6	3.09
8	0 7 1	0.1032	0.1027	7	3.02
9	2 8 0	0.1133	0.1137	4	2.88
10	3 6 0	0.1273	0.1274	4	2.72
11	1 9 1	0.1395	0.1391	2	2.59
12	1 11 0	0.1528	0.1533	3	2.48
13	1 9 $\bar{1}$ 3 0 $\bar{1}$	0.1622	0.1620 0.1621	7	2.41
14	3 2 $\bar{1}$	0.1679	0.1669	1	2.36
15	3 10 0	0.2030	0.2035	1	2.15
16	1 0 $\bar{2}$	0.2091	0.2092	2	2.12
17	1 5 $\bar{2}$	0.2392	0.2389	2	1.98
18	0 13 1	0.2470	0.2454	3	1.95
19	2 11 2	0.3159	0.3151	3	1.72

Originally the author tried to calculate the dimensions of the unit cell of manganese-hoernesite, assuming the dimensions of the cell to be similar to those of vivianite. It was impossible, however, to index the diffraction lines of the powder-photograph from this assumption. On the other hand the indexing could be quite satisfactory, if one assumed the dimensions of the unit cell to resemble those of bobierrite, as determined by T. BARTH (1937).

The following values of the dimensions of the unit cell of manganese-hoernesite were obtained ($\pm$ 0.05 Å).

$$a = 10.38\ \text{Å},\ b = 28.09\ \text{Å},\ c = 4.774\ \text{Å},\ \beta = 105^\circ 40'$$

Oscillation photographs around the *c*-axis gave the same *c*-value. The volume of the unit cell is 1340 Å^3. The number of molecules in the cell is four. No detailed structural investigation of manganese-hoernesite has yet been made on account of the difficulties in finding suitable crystals for Weissenberg photographs. Attempts have been made, but the crystals were bent and distorted and composed of several fibres of slightly different orientation.

The investigation shows that manganese-hoernesite cannot be isomorphous with the members of the vivianite group (symplesite, vivianite, annabergite, erythrite and koettigite), which all belong to the space-group C_{2h}^3–$C2/m$. In this space-group there are only $(h\,k\,l)$-reflections with $h + k = 2\,n$ and $(h\,0\,l)$-reflections with $h = 2\,n$. These conditions are not satisfied in this case.

It seems more likely to assume that manganese-hoernesite belongs to the same space-group as bobierrite, which probably is C_{2h}^5–$P\,2_1/c$, according to T. BARTH. In this space-group all (hkl)-reflections, ($h0l$)-reflections with $l = 2n$ and ($0k0$)-reflections with $k = 2n$ are present. These conditions agree with the indexing of manganese-hoernesite, if one assumes that the line no. 13 in the photograph ($\sin^2\theta = 0.1622$) has the index $(19\bar{1})$ and (301) is extinguished.

The unit cell dimensions of manganese-hoernesite are compared with those of bobierrite (as measured by T. Barth) in table 2. There are great similarities between these two minerals. It is interesting to observe, that b_0 of bobierrite and manganese-hoernesite is about twice as large as b_0 of members of the vivianite-group.

Table 2

Mineral	Bobierrite	Hoernesite	Manganese-hoernesite
Composition	$Mg_3(PO_4)_2 \cdot 8H_2O$	$Mg_3(AsO_4)_2 \cdot 8H_2O$	$(MnMg)_3(AsO_4)_2 \cdot 8H_2O$
Symmetry	Monoclinic	Monoclinic	Monoclinic
Space group	C_{2h}^5 $P\,2_1/c$	C_{2h}^5–$P\,2_1/c$?	C_{2h}^5 –$P\,2_1/c$?
a_0	9.946		10.38
b_0	27.654		28.09
c_0	4.639		4.774
β	104°01′		105°40′
Cell volume	1238.0 Å^3		1340 Å^3
Cell contents	4 mol.		4 mol.
Spec. gravity (measured)		2.73	
Spec. gravity (calculated)	2.17		2.76
Cleavages	(010)	(010)	(010)
Optical sign	+	+	+
2 V	71°	60°	65–70°
n_X	1.510	1.563	1.579
n_Y	1.520	1.571	1.589
n_Z	1.543	1.596	1.609
X		b	b
Y	b		
Z	to $c = 30°$	to $c = 31°$	to $c = 31°$

Chemical composition. A chemical analysis of manganese-hoernesite (Nr 251065, Flink's No 310) has been performed by Dr. R. Blix. The result of this analysis is shown in table 3. The sample was contaminated with a carbonate, probably rhodochrosite.

The molecular proportions are $As_2O_5 : (Mn,Mg)O : H_2O = 1 : 2.97 : 8.02$, corresponding to the formula $(Mn,Mg)_3(AsO_4)_2 \cdot 8H_2O$. This formula agrees with the formula of hoernesite $Mg_3(AsO_4)_2 \cdot 8H_2O$, but with a large portion of magnesium replaced by manganese. The atomic proportion Mg : Mn is about 2 : 3.

A determination of the magnesium and manganese contents of another manganiferous hoernesite (sample No 25347, Flink's No 31) has also been performed by Dr. Blix. The values obtained are shown in Table 3, from which it can be seen that the Mg : Mn proportion is about 5 : 3. The two minerals analysed can be chemically characterised as composed of various proportions of the molecules $Mg_3(AsO_4)_2 \cdot 8H_2O$ and $Mn_3(AsO_4)_2 \cdot 8H_2O$, which are the end-members of an isomorphous series. The percentage of these two molecules in the minerals analysed are given in table 4.

Table 3

	Manganese-hoernesite		Manganiferous hoernesite	
	%	Mol. prop.	%	Mol. prop.
As_2O_5	40.78	0.1774 = 1		
MnO	22.87	0.2918[2] } = 2.97	14.8	0.2087
MgO	9.47	0.2349	15.0	0.3722
CO_2	1.35[1]			
H_2O	25.64	1.4231 = 8.02		
	100.11			

[1] CO_2 probably enters in rhodochrosite together with excess of MnO.

[2] For 20.70 % MnO after correction for CO_2

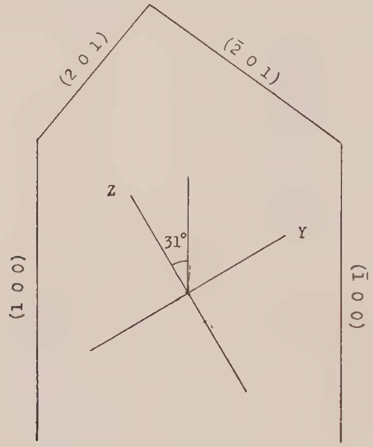

Figure 1.

Optical properties. The optical plane is perpendicular to (010). Z $\wedge$ c = 31°. X = b. The optical angle (2 V) is 65—70°. The optical sign is positive. The optical orientation is shown in figure 1. The optical data of manganese-hoernesite are compared with those of hoernesite and bobierrite in Table 2.

The optical properties of hoernesite and manganese-hoernesite are similar to those of bobierrite. There is however a rather peculiar divergence in the optical orientation, which BARTH has already pointed out.

The refractive indices of hoernesites with various percentages of manganese and magnesium are shown in table 4. The percentages of manganese and magnesium are given in mol. percent of the molecules $Mg_3(AsO_4)_2 \cdot 8H_2O$ and $Mn_3(AsO_4)_2 \cdot 8H_2O$. The diagram shows that the refractive indices will be higher, when the percentage of manganese increases.

Occurrence and paragenesis. The manganese-hoernesite occurs in fissures in a grayish-white skarn rock in the Långban mine. Together with the manganese-hoernesite, there is found small brown and yellow-brown, platy, elongated crys-

Table 4

The refractive indices in relation to the chemical composition of hoernesite and manganese-hoernesite.

	Molecules of $Mg_3(AsO_4)_2 \cdot 8 H_2O$ in percent	Molecules of $Mn_3(AsO_4)_2 \cdot 8 H_2O$ in percent	n_X	n_Y	n_Z
Hoernesite (Joachimsthal, Larsen)	100	—	1.563	1.571	1.596
Manganiferous hoernesite (Långban, Nr 25347)	64.0	36.0	1.576	1.587	1.606
Manganese-hoernesite (Långban, Nr 251065)	44.6	55.4	1.579	1.589	1.609

tals, usually forming a coating on the fissures. They have crystallographic and optical properties resembling allodelphite from Långban, which has been described by P. QUENSEL and H. v. ECKERMANN (1930). The maximum refractive index of the brown mineral is 1.75. This value agrees well with the refractive index of allodelphite. The maximum refractive index of the yellow-brown mineral is somewhat higher (1.77). According to C. HURLBUT Jr (1937) allodelphite described by QUENSEL and ECKERMANN, is a synadelphite with some quartz as an impurity. In one sample a green mineral was observed together with manganese-hoernesite. This mineral resembles a green manganese-arsenite from Långban, not yet described.

The manganese-hoernesite and the minerals just mentioned are sometimes developed on a rough crust of an amorphous, gray-white to pink mineral, probably rhodochrosite.

On account of the very slight differences in optical properties between manganiferous hoernesite and manganese-hoernesite there are great difficulties in determining these minerals in every case. There are probably successive transition types between these two minerals mentioned.

The fissure minerals seem to have crystallized in the following succession. At first rhodochrosite has been formed as a coating on the fissures. On this coating the other minerals mentioned have crystallized. Often one can observe hoernesite and manganese-hoernesite, covering the brown or yellow-brown mineral, which probably is allodelphite or synadelphite.

This mineral paragenesis belongs to the last period of mineral crystallization of the Långban mine and was formed at very low temperatures. To this period all fissure minerals of the Långban mine are referred, according to the classification of N. H. MAGNUSSON (1930).

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The crystal structures of kröhnkite, $CuNa_2(SO_4)_2 \cdot 2\,H_2O$ and brandtite, $MnCa_2(AsO_4)_2 \cdot 2\,H_2O$

By BERTIL DAHLMAN

With 9 figures in the text

Introduction

C. W. WOLFE (1940) presented a classification of the arsenates and phosphates of the type $A_3(XO_4)_2 \cdot nH_2O$, based on an investigation of their chemical and physical properties, together with an X-ray determination of the lattice constants. He demonstrated that all minerals containing the same number of water molecules show certain definite similarities, which are only slightly modified by a variation of the cations and the radicals, and he suggested that the minerals might be separated into families on the basis of the number of water molecules present. Further he divided every family into groups based upon similarity of crystal symmetry.

His family $A_3(XO_4)_2 \cdot 2\,H_2O$ contains two triclinic minerals, fairfieldite and collinsite and two monoclinic, roselite and brandtite. As a result of his investigation, WOLFE stated that the two monoclinic members of the family are isostructural and closely related to the minerals of the triclinic group. In the unit cells of the triclinic and monoclinic species a and c are practically equal, while b is doubled in the monoclinic species. The higher symmetry is obtained directly from the lower by twinning of the lattice, a single plane of reflexion producing monoclinic symmetry with the doubled volume.

Studying WOLFE's work the present author found that the mineral kröhnkite $CuNa_2(SO_4)_2 \cdot 2\,H_2O$ might be isostructural with roselite and brandtite[1], and furthermore that all three might be closely related to TUTTON's salts $M'_2M''(XO_4)_2 \cdot 6\,H_2O$ where $M' = $ K, Rb, Cs, (NH_4), Tl, and $M'' = $ Mg, Zn, Cd, Cu, Ni, Co, Fe, Mn and $X = $ S, Se.

The purposes of this investigation are:

1. To determine the crystal structures of kröhnkite and brandtite
2. To study the structural relation between kröhnkite and the minerals of the $A_3(XO_4)_2 \cdot 2\,H_2O$ family.
3. To study the relation between the structures of the minerals already mentioned and those of the TUTTON's salts.

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[1] Quite recently MACHATSCHKI (1950) in a short notice published in Tschermak's Min. Mitth. pp 424 asserted that kröhnkite might be isomorphous with roselite and brandtite.

Earlier investigations

Roselite was named by LÉVY (1824), who described the mineral as orthorombic. This interpretation was accepted until SCHRAUF (1874) found that roselite was triclinic with the axial ratio $a:b:c = 0.45360:1:0.65604$; $\alpha = 90°34'$, $\beta = 91°$, $\gamma = 89°20'$. Crystals were very small and, as explained by SCHRAUF, combined according to a number of twinning laws with embedded twinning lamellae. Cleavage was perfect, parallel to the macrodiagonal. The chemical composition as found by WINKLER (1877) is $(Ca, Co, Mg)_3As_2O_8 \cdot 2\,H_2O$. A. E. NORDENSKIÖLD (1888) reported a new arsenate found at Harstigen in Värmland (Sweden) which he named brandtite. A closer description of brandtite was made by LINDSTRÖM (1891) who, in addition to publishing an analysis of the mineral, pointed out the close chemical relationship to roselite. The chemical composition was found to be $Ca_2MnAs_2O_8 \cdot 2\,H_2O$. In the same paper NORDENSKIÖLD reported some crystallographical facts, and stated that brandtite was triclinic and isomorphic with roselite. AMINOFF (1919), by a thorough study of the crystallography of brandtite, proved that NORDENSKIÖLD's designation of brandtite as triclinic was in error, and established a monoclinic symmetry. According to AMINOFF brandtite is monoclinic holoedric with the axial ratio $a:b:c = 0.8720:1:0.4475:\beta = 80°23'$. He further found, that cleavage was distinct parallel to (0 1 0) and twinning with (1 0 0) as twinning plane was not rare. AMINOFF pointed out the close relation between brandtite and roselite but stated "Die Richtigkeit der Symmetriebestimmungen SCHRAUFS in Frage zu stellen, dürfte wohl kaum angebracht sein . . .". A new investigation of the crystallography of roselite was made by PEACOCK (1936). Without cognizance of AMINOFF's earlier work on brandtite PEACOCK found that roselite was monoclinic with the axial ratio $a:b:c = 0.8780:1:0.4398:\beta = 100°53'$. He further found that single crystals of roselite were very rare; nearly all crystals were twinned by reflection in (1 0 0), which is the plane composition surface separating pairs of symmetrical individuals. An X-ray investigation of the two minerals, made by WOLFE (1940) confirmed AMINOFF's and PEACOCK's results. The *a*-axes, however, are only the half of that found by the earlier workers.

Both minerals are monoclinic prismatic, space group $C_{2h}^5 - P2_1/c$.

Brandtite $a = 5.65$ Å, $b = 12.80$ Å, $c = 5.65$ Å, $\beta = 99°30'$

Roselite $a = 5.60$ Å, $b = 12.80$ Å, $c = 5.60$ Å, $\beta = 100°45'$

Recently GEIGER (1948) described a new variety of brandtite found in Graubünden (Switzerland) containing about 3 per cent MgO. Without cognizance of WOLFE's work GEIGER gave the following lattice constants based on powder photographs, Fe-K_α-radiation and rotation photographs with (1 0 0) and (0 0 1) as rotation axis.

$a = 6.26$ Å

$b = 5.40$ Å $\beta = 92°$

$c = 5.69$ Å.

Kröhnkite was first described by DOMEYKO (1876) and later by DARAPSKY (1889). DARAPSKY described the mineral as monoclinic with the axial ratio

$a:b:c: = 0.44625:1:0.43521$, $\beta = 72°41'$, and with distinct cleavage parallel to (010) and (110). CH. PALACHE and C. H. WARREN (1908) gave a new description of the mineral. These authors observed that crystals of kröhnkite are often twinned, and believing that (001) was the twinning plane, they changed DARAPSKY's orientation and thus found the axial ratio $a:b:c: = 0.5229:1:0.4357$, $\beta = 56°17'20''$. Based on an X-ray determination of the lattice constants of kröhnkite by W. E. RICHMOND, PALACHE (1936) made a re-examination of the mineral and found that a mistake had been made in changing DARAPSKY's original orientation. A wealth of well crystallized kröhnkite was examined and a number of new forms revealed. PALACHE then described kröhnkite as monoclinic prismatic —2/m with the axial ratio $a:b:c = 0.4586:1:0.4357$, $\beta = 108°30'$. Cleavage is perfect, parallel to (010) and very imperfect, parallel to (101). No trace of cleavage parallel to (110) as recorded by DARAPSKY was found. The twinning described in 1908 as basal is now referred to ($\bar{1}01$).

The result of the X-ray study of RICHMOND is in perfect agreement with PALACHE's morphological determination. The lattice constants according to RICHMOND are:

$$a = 5.78\ \text{Å}$$

$$b = 12.58\ \text{Å} \quad \beta = 108°30'$$

$$c = 5.48\ \text{Å}$$

$$a_0 : b_0 : c_0 : = 0.4593 : 1 : 0.4359$$

The space group is $C_{2h}^5 - P2_1/c$. The unit cell contains 2 molecules. The chemical composition of the mineral was determined by DOMEYKO and later confirmed by WARREN to be $CuNa_2(SO_4)_2 \cdot 2\,H_2O$.

The double sulphates and selenenates $M''M'_2(XO_4)_2 \cdot 6\,H_2O$, where $M'' = $ Mg, Zn, Cd, Cu, Ni, Co, Fe, Mn, and $M' = $ K, Rb, Cs, Tl, (NH_4), have been called TUTTON's salts in honour of A. E. H. TUTTON, who in the years 1890—1928 made excellent investigations of the optical and physical properties of these compounds. Some members of TUTTON's salts have been investigated by means of X-rays by HOFMANN (1931), who proposed atomic arrangements of the compounds. JENSEN (1948), in his work on salt-hydrates found that the structure of TUTTON's salts proposed by HOFMANN must be in error. The water molecules in the structures according to HOFMANN, are placed on straight lines connecting two cations, which JENSEN considers to be an impossible arrangement.

A summary of the properties of the minerals described above is given in Table I.

Material

The present writer had the advantage of having at his disposal the whole collection of brandtite crystals earlier measured by AMINOFF (1919). A preliminary investigation showed A:s crystal No. 15 to be suitable. This crystal is prismatic and elongated parallel to the c-axis. It was cut in order to get an approximate cylinder (diameter 0.4 mm) suitable for diagrams around the c-axis. A crystal from Chuquicamata with almost the same dimensions was used for the investigation of kröhnkite.

Table

Mineral	Fairfieldite		Roselite	
Composition	$(MnFe)Ca_2(PO_4)_2 \cdot 2\,H_2O$		$(CoMg)Ca_2(AsO_4)_2 \cdot 2\,H_2O$	
Crystal System	Triclinic		Monoclinic	
Crystal Class	Pinacoidal		Prismatic	
Space Group	C_i^1—$P\,\bar{1}$		C_{2h}^5—$P\,2_1/c$	
a_0 Å.	5.77		5.60	
b_0 Å.	6.56		12.80	
c_0 Å.	5.47		5.60	
$a_0 : b_0 : c_0$	0.8791 : 1 : 0.8331		0.4374 : 1 : 0.4374	
α	102°05′			
β	108°42½′		100°45′	
γ	90°05½′			
Morphology $a : b : c$	Unsatisfactory		0.8780 : 1 : 1.4398	
Cell Volume	197.2 cub Å		394.36 cub Å	
Cell Contents	1 molecule		2 molecules	
Sp. G. Meas.	3.082		3.695	
Sp. G. Calc.	3.09		3.645	
Cleavages	(001) (010) $(1\bar{1}0)$		(010)	
Hardness	3.5		3.5	
Optical Sign	+		+	
2 V	86°		60°	
$r : v$	$r > v$		$r < v$	
			pink	dark
Indices of Refraction α	1.633		1.694	1.725
β	1.641		1.704	1.728
γ	1.652		1.719	1.735
	Φ	ϱ		
X	120°	60°	to [001] 1°	[010]
Y	—102°	36°	[010]	to [001], 12°–20°
Z	18°	69°		
Locality	Buckfield		Schneeberg	

Unit cell and space group

Equi-inclination photographs of both minerals were taken around the c-axes using unfiltered copper radiation. The unit cell dimensions found are, within the limits of error, equal to those found by WOLFE for brandtite $a_0 = 5.65$ Å, $b_0 = 12.80$ Å, $c_0 = 5.65$ Å, $\beta = 99°30'$ and by RICHMOND for kröhnkite $a_0 = 5.78$ Å, $b_0 = 12.58$ Å, $c_0 = 5.48$ Å, $\beta = 108°30'$. A powder photograph of kröhnkite was taken using unfiltered iron radiation, but with these particular lattice constants, no greater accuracy can be attained by measurements of powder photographs taken with a camera with normal radius. The cell dimensions found by GEIGER (1948) are in error, but the powder photogram published by him (Table II in this paper) can be interpreted fairly well, using the constants given above. This is shown by a comparison of Tables II, IV and Table V, in this paper.

I

Brandtite	Kröhnkite	Picromerite	Cyanochroite
$MnCa_2(AsO_4)_2 \cdot 2\,H_2O$	$CuNa_2(SO_4)_2 \cdot 2\,H_2O$	$MgK_2(SO_4)_2 \cdot 6\,H_2O$	$CuK_2(SO_4)_2 \cdot 6\,H_2O$
Monoclinic	Monoclinic	Monoclinic	Monoclinic
Prismatic	Prismatic	Prismatic	Prismatic
$C_{2h}^5 - P\,2_1/c$	$C_{2h}^5 - P\,2_1/c$	$C_{2h}^5 - P\,2_1/c$	$C_{2h}^5 - P\,2_1/c$?
5.65	5.78	9.04	
12.80	12.58	12.24	
5.65	5.48	6.095	
0.4412 : 1 : 4412	0.4593 : 1 : 0.4359	0.7386 : 1 : 0.4980	
99°30′	108°30′	104°48′	104°28′
0.8720 : 1 : 0.4475	0.4586 : 1 : 0.4357	0.7413 : 1 : 0.4993	0.7490 : 1 : 0.5088
403.00 cub Å	378.01 cub Å	396.46 cub Å	396,46
2 molecules	2 molecules	2 molecules	2 molecules ?
3.671	2.90 ± 0.02	2.028	2.224
3.700	2.95		
(010)	(010) ($\bar{1}$01)	(201)	(201)
3.5	3	2.5	
+	—	+	+
23°	78°	48°	46°
$r < v$	$r < v$	$r > v$	$r > v$
Falotta			
1.707 1.709	1.544	1.4602	1.4856
1.711	1.578	1.4633	1.4864
1,729 1.725	1.601	1.4768	1.5020
[010]	[001] 48°	to [001] 13°38′	to [001] 18°53′
to [001] 8°	[010]		
	1°60′	to [100] 1°10′	to [100] 4°5′
Harstigen	Chuquicamata		

The Weissenberg photographs obtained, registered the reflections $h\,k\,0$ and $h\,k\,1$. By studying the systematic extinctions it was found that reflections $0\,k\,0$ are only present for $k = 2\,n$, and that reflections $h\,0\,1$ are absent. Based on these facts the space group determined by WOLFE and RICHMOND $C_{2h}^5 - P\,2_1/c$, and fixed by the following determinative reflections:

$$h\,k\,l - \text{all present}$$
$$h\,0\,l - l \text{ even}$$
$$0\,k\,0 - k \text{ even}$$

was accepted.

Table II

Powder photographs of brandtite according to TH. GEIGER. Fe-K_α-radiation.

Intensities	d	$\frac{\sin \theta}{\lambda}$	Intensities	d	$\frac{\sin \theta}{\lambda}$
s	5.08	0.098	sss	1.890	0.265
sss	4.89	.101	sss	1.865	.268
s	3.74	.134	sss	1.835	.272
ss	3.40	.147	m	1.813	.276
ms	3.33	.150	m	1.730	.289
ms	3.21	.156	ss	1.706	.293
s	3.13	.160	s	1.622	.308
mst	2.98	.168	ss	1.578	.317
mst	2.785	.180	ss	1.560	.321
m	2.606	.192	sss	1.538	.325
ms	2.325	.215	s	1.500	.333
ms	2.256	.222	sss	1.448	.345
m	2.106	.237	s	1.398	.358
sss	2.058	.243	ss	1.377	.363
sss	2.005	.249	m	1.208	.414

Atomic positions

The atomic positions and symmetry elements of the space-group $C_{2h}^5 - P\,2_1/c$ are (according to I. T. 1935):

$$2: (a)\ 0\,0\,0;\ 0\,\tfrac{1}{2}\,\tfrac{1}{2}\quad (b)\ \tfrac{1}{2}\,0\,0;\ \tfrac{1}{2}\,\tfrac{1}{2}\,\tfrac{1}{2}\quad (c)\ 0\,0\,\tfrac{1}{2};\ 0\,\tfrac{1}{2}\,0.\quad (d)\ \tfrac{1}{2}\,0\,\tfrac{1}{2};\ \tfrac{1}{2}\,\tfrac{1}{2}\,0.$$

$$4: (e)\ x\,y\,z;\ \bar{x}\,\bar{y}\,\bar{z};\ \bar{x},\ \tfrac{1}{2}+y,\ \tfrac{1}{2}-z;\ x,\ \tfrac{1}{2}-y,\ \tfrac{1}{2}+z.$$

Point symmetry:

$$C_i - \bar{1} \text{ in } (a), (b), (c), (d).$$

$$C_1 - 1 \text{ in } (e).$$

The cells contain two molecules $CuNa_2(SO_4)_2 \cdot 2\,H_2O$ or, $MnCa_2(AsO_4)_2 \cdot 2\,H_2O$. Thus we have to place, in all, two Cu(Mn), four S(As), four Na(Ca), sixteen oxygen atoms and four H_2O groups into the cell.

The two copper (manganese) atoms must be placed in position (*a*) — (*d*).

Assuming tetrahedral groups of oxygen atoms around S(As), these atoms cannot lie at a centre of symmetry, but must be placed in a four-fold position (*e*).

The sodium (calcium) atoms can either be placed in two two-fold positions or in one four-fold position.

For oxygen there are the following possibilities:

$$16\ O \text{ in } \begin{cases} 4+4+4+4 \\ 4+4+4+2+2 \end{cases}$$

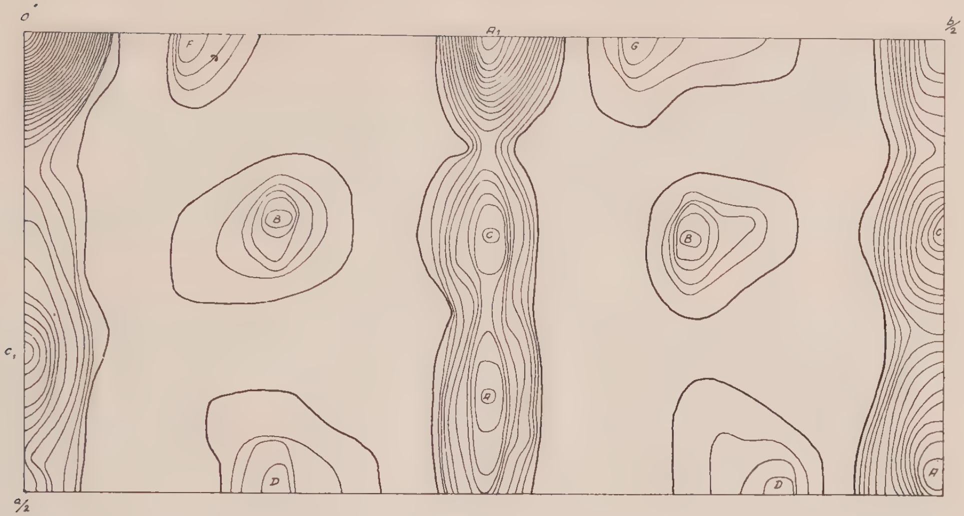

Fig. 1. Patterson function $P\ (u, v)$ of brandtite, monoclinic $MnCa_2(AsO_4)_2 \cdot 2\,H_2O$. Contour lines are drawn at height differences of 50 units.

It was preliminarily assumed that Cu(Mn) might be placed in the same position as M^{II} in TUTTON's salts (a) $0\,0\,0$; $0\,\frac{1}{2}\,\frac{1}{2}$, and all other atoms in four-fold positions (e).

Patterson function

All intensities were visually estimated from Weissenberg photographs (Cu-K-radiation) with rotation around the c-axis. Relative $|F^2|$ values were calculated from the estimated intensity-values by dividing by the polarization and Lorentz factors. These factors were as usual combined into the factor

$$\frac{1 + \cos^2 2\,\Theta}{\sin 2\,\Theta}$$

No correction for absorption was introduced. The parameters of the metal atoms and the arsenic atoms of brandtite were determined approximately by means of a Patterson function on (0 0 1), $P\ (u, v)$.

On the assumption that the crystal structure of brandtite is closely related to those of TUTTON's salts, the Patterson function was interpreted by using the vectors of the heavy atoms found by HOFMANN for $Mg(NH_4)_2\,(SO_4)_2 \cdot 6\,H_2O$. The highest maxima (A) are ascribed to vectors As-As, and maxima (B) to vectors Mn-As. The vectors As-Ca are represented by maxima C, Mn-Ca by maxima D. Maximum A_1 is built up by vectors As-As co-operating with vectors Ca-Ca.

Maxima A and B define the x and y parameters of As to be $x \sim 0.75$ and $y \sim 0.125$. C_1 lying approximately at the same y-distance as A, together with D and E, define the parameters of Ca to be $x \sim 0.42$ and $y \sim 0.125$. Finally two small maxima F and G must be ascribed to one or two oxygen atoms or water molecules with the same x-parameters as As.

The parameters

Assuming that brandtite and kröhnkite are isostructural the same approximative parameters are used for kröhnkite.

$$\mathrm{Ca(Na)}\quad x \sim 0.42 \quad y \sim 0.125$$

$$\mathrm{As(S)}\quad x \sim 0.75 \quad y \sim 0.125$$

and one or two oxygen atoms or water groups with $x \sim 0.75$.

The corresponding exact parameters and the parameters of the oxygen atoms and the water groups were found by the method of trial and error, based on the following assumptions:

1. Manganese (Copper) lying in centres of symmetry must be surrounded either by four or six oxygen atoms or water groups in the corners of quadrates or octahedra respectively. Eight co-ordination for Mn and Cu is very improbable. The divalent manganese and copper ions are almost always found in six co-ordination to oxygen and water, and it was assumed that Mn(Cu) is surrounded by six oxygen atoms or by four oxygen atoms and two water molecules, lying at the corners of an octahedron. The distances Mn-O and Cu-O were assumed to be 2.20 Å and 2.12 Å respectively.

2. The presence of tetrahedral groups of oxygen round arsenic and sulphur in arsenates and sulphates is a well-known fact. The distances As-O and S-O were assumed to be 1.64 Å and 1.50 Å respectively.

3. The distance Ca-O and Na-O are found to be approximately 2.46 Å in most structures.

The parameter corrections were controlled by means of Fourier synthesis with the relative electron density (x, y) projected on $(0\,0\,1)$. The z-parameters are determined geometrically from the carefully determined x and y-parameters, and checked against the observed $|F|$ values. The $|F|$ values for the $h\,k\,1$ reflections are calculated from the estimated intensities by the method given by Lu (1943).

The final parameters are:

Table III

Final parameters

Brandtite.

2 Mn	in (a)	$x = 0$	$y = 0$	$z = 0$
4 Ca	in (e)	$x = 0.428$	$y = 0.120$	$z = 0.253$
4 As	in (e)	$x = 0.777$	$y = 0.122$	$z = 0.566$
4 O_{I}	in (e)	$x = 0.048$	$y = 0.165$	$z = 0.522$
4 O_{II}	in (e)	$x = 0.694$	$y = 0.055$	$z = 0.816$
4 O_{III}	in (e)	$x = 0.756$	$y = 0.030$	$z = 0.336$
4 O_{IV}	in (e)	$x = 0.559$	$y = 0.208$	$z = 0.566$
4 H_2O	in (e)	$x = 0.208$	$y = 0.136$	$z = 0.935$

Kröhnkite.

2 Cu	in (a)	$x = 0$	$y = 0$	$z = 0$
4 Na	in (e)	$x = 0.427$	$y = 0.126$	$z = 0.237$
4 S	in (e)	$x = 0.766$	$y = 0.118$	$z = 0.578$
4 O_{I}	in (e)	$x = 0$	$y = 0.165$	$z = 0.480$
4 O_{II}	in (e)	$x = 0.733$	$y = 0.049$	$z = 0.803$
4 O_{III}	in (e)	$x = 0.733$	$y = 0.049$	$z = 0.358$
4 O_{IV}	in (e)	$x = 0.571$	$y = 0.186$	$z = 0.622$
4 H_2O	in (e)	$x = 0.173$	$y = 0.130$	$z = 0.987$

A comparison between observed and calculated intensities is given in Tables IV to Table VII.

Table IV

Weissenberg photograph of Brandtite, monoclinic $MnCa_2(AsO_4)_2 \cdot 2\,H_2O$. Rotation axis [001]. Zero layer line. Cu-K-radiation.
Comparison between observed and calculated intensities.

h k l	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.	*h k l*	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.
1 0 0	0.089	—	4	3 1 0	0.270	92	81
2 0 0	.179	44	49	3 2 0	.278	33	42
3 0 0	.268	22	18	3 3 0	.292	133	112
4 0 0	.358	109	102	3 4 0	.309	100	87
5 0 0	.447	100	98	3 5 0	.331	50	52
6 0 0	.537	49	63	3 6 0	.355	23	30
7 0 0	.626	—	4	3 7 0	.382	66	62
0 2 0	.078	44	62	3 8 0	.416	38	31
0 4 0	.156	140	131	3 9 0	.442	59	58
0 6 0	.234	48	41	3.10.0	.473	—	4
0 8 0	.313	160	138	3.11.0	.501	80	66
0.10.0	.391	46	34	3.12.0	.539	78	65
0.12.0	.469	135	90	3.13.0	.574	19	19
0.14.0	.547	—	4	3.14.0	.609	12	22
0.16.0	.625	98	91	4 1 0	.358	12	15
1 1 0	.097	58	58	4 2 0	.364	40	38
1 2 0	.118	34	48	4 3 0	.375	13	8
1 3 0	.147	81	75	4 4 0	.389	19	19
1 4 0	.180	39	42	4 5 0	.406	—	10
1 5 0	.215	20	21	4 6 0	.426	14	28
1 6 0	.251	59	46	4 7 0	.449	—	4
1 7 0	.288	34	39	4 8 0	.474	67	66
1 8 0	.325	—	8	4 9 0	.500	—	4
1 9 0	.363	45	31	4.10.0	.529	13	18
1.10.0	.401	12	5	4.11.0	.558	12	10
1.11.0	.439	63	54	4.12.0	.589	31	31
1.12.0	.477	64	57	5 1 0	.447	10	12
1.13.0	.516	43	30	5 2 0	.452	10	10
1.14.0	.554	15	20	5 3 0	.460	10	10
1.15.0	.593	56	48	5 4 0	.472	59	55
1.16.0	.631	—	1	5 5 0	.486	—	4
2 1 0	.182	—	14	5 6 0	.503	14	21
2 2 0	.194	17	17	5 7 0	.522	—	8
2 3 0	.213	52	50	5 8 0	.548	96	96
2 4 0	.237	100	92	5 9 0	.567	8	9
2 5 0	.264	34	37	5.10.0	.592	32	36
2 6 0	.294	42	42	5.11.0	.619	19	23
2 7 0	.326	67	63	6 1 0	.536	20	20
2 8 0	.360	24	26	6 2 0	.540	—	15
2 9 0	.385	30	28	6 3 0	.547	45	54
2.10.0	.429	55	40	6 4 0	.556	59	72
2.11.0	.465	60	46	6 5 0	.575	27	31
2.12.0	.501	87	75	6 6 0	.583	19	20
2.13.0	.538	—	8	6 7 0	.600	62	59
2.14.0	.575	19	28	6 8 0	.619	25	31
2.15.0	.612	46	38	7 1 0	.624	19	16
				7 2 0	.628	14	14

Table V

Weissenberg photograph of Brandtite, monoclinic $MnCa_2(AsO_4)_2 \cdot 2\,H_2O$. Rotation axis [001]. First layer line. Cu-K-radiation.
Comparison between observed and calculated intensities.

h k l	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.	*h k l*	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.
0 1 1	0.097	33	32	2.14.1	0.585	23	25
0 2 1	.118	—	4	2.15.1	.624	24	25
0 3 1	.147	116	125	3 1 1	.300	62	73
0 4 1	.180	10	10	3 2 1	.308	76	82
0 5 1	.215	54	61	3 3 1	.320	7	13
0 6 1	.251	11	13	3 4 1	.336	—	6
0 7 1	.286	—	2	3 5 1	.356	—	0
0 8 1	.325	—	0	3 6 1	.379	78	92
0 9 1	.363	33	28	3 7 1	.404	20	32
0.10.1	.401	—	7	3 8 1	.432	—	7
0.11.1	.439	46	46	3 9 1	.461	55	65
0.12.1	.478	12	16	3.10.1	.491	50	61
0.13.1	.516	95	73	3.11.1	.523	3	3
0.14.1	.555	—	0	3.12.1	.555	8	12
0.15.1	.593	7	7	3.13.1	.589	19	22
0.16.1	.626	9	8	3.14.1	.623	30	35
1 1 1	.143	74	69	4 1 1	.386	47	46
1 2 1	.156	184	175	4 2 1	.392	30	33
1 3 1	.180	—	5	4 3 1	.402	112	98
1 4 1	.208	—	4	4 4 1	.415	—	7
1 5 1	.239	—	2	4 5 1	.431	105	90
1 6 1	.272	150	146	4 6 1	.450	—	3
1 7 1	.306	18	18	4 7 1	.472	38	34
1 8 1	.341	30	14	4 8 1	.495	—	9
1 9 1	.377	57	64	4 9 1	.521	62	59
1.10.1	.429	122	112	4.10.1	.548	—	11
1.11.1	.451	—	3	4.11.1	.576	36	50
1.12.1	.488	25	26	5 1 1	.473	9	11
1.13.1	.526	—	7	5 2 1	.478	25	34
1.14.1	.564	60	76	5 3 1	.486	—	7
1.15.1	.602	44	50	5 4 1	.497	—	3
1.16.1	.640	17	17	5 5 1	.511	—	9
2 1 1	.217	34	35	5 6 1	.527	27	34
2 2 1	.227	38	46	5 7 1	.545	20	24
2 3 1	.244	30	33	5 8 1	.566	—	8
2 4 1	.265	—	3	5 9 1	.589	14	25
2 5 1	.289	12	14	5.10.1	.613	34	44
2 6 1	.317	38	35	6 1 1	.555	25	42
2 7 1	.347	60	72	6 2 1	.559	43	60
2 8 1	.382	7	12	6 3 1	.567	—	4
2 9 1	.411	61	65	6 4 1	.576	16	28
2.10.1	.445	9	10	6 5 1	.587	—	2
2.11.1	.480	—	5	6 6 1	.601	46	58
2.12.1	.515	—	0	6 7 1	.618	36	50
2.13.1	.551	14	11	6 8 1	.636	—	1

Table V (cont.)

$h\,k\,l$	$\frac{\sin\theta}{\lambda}$	$\lvert F\rvert$ obs.	$\lvert F\rvert$ calc.	$h\,k\,l$	$\frac{\sin\theta}{\lambda}$	$\lvert F\rvert$ obs.	$\lvert F\rvert$ calc.
$\bar{1}\,1\,1$	0.122	28	28	$\bar{3}.13.1$	0.575	—	3
$\bar{1}\,2\,1$	.140	55	59	$\bar{3}.14.1$	.610	35	42
$\bar{1}\,3\,1$	.165	88	101	$\bar{3}.15.1$	.645	45	55
$\bar{1}\,4\,1$	.195	—	3	$\bar{4}\,1\,1$	.358	8	12
$\bar{1}\,5\,1$	.227	92	110	$\bar{4}\,2\,1$	.364	115	107
$\bar{1}\,6\,1$	.262	13	20	$\bar{4}\,3\,1$	.374	6	11
$\bar{1}\,7\,1$	.297	10	8	$\bar{4}\,4\,1$	.388	10	15
$\bar{1}\,8\,1$	.333	—	1	$\bar{4}\,5\,1$	.406	12	19
$\bar{1}\,9\,1$	.370	13	7	$\bar{4}\,6\,1$	.426	64	53
$\bar{1}.10.1$	.408	44	37	$\bar{4}\,7\,1$	.448	11	12
$\bar{1}.11.1$	.445	46	47	$\bar{4}\,8\,1$	.473	—	9
$\bar{1}.12.1$	.483	—	1	$\bar{4}\,9\,1$	.500	43	38
$\bar{1}.13.1$	.521	69	62	$\bar{4}.10.1$	.528	57	55
$\bar{1}.14.1$	.559	26	29	$\bar{4}.11.1$	.558	15	28
$\bar{1}.15.1$	.597	22	15	$\bar{4}.12.1$	.588	—	2
$\bar{1}.16.1$	.636	9	12	$\bar{4}.13.1$	.620	10	16
$\bar{2}\,1\,1$	.191	155	120	$\bar{5}\,1\,1$	.445	33	32
$\bar{2}\,2\,1$	.203	140	106	$\bar{5}\,2\,1$	.450	28	46
$\bar{2}\,3\,1$	.221	—	5	$\bar{5}\,3\,1$	.458	71	83
$\bar{2}\,4\,1$	.244	32	36	$\bar{5}\,4\,1$	.470	15	18
$\bar{2}\,5\,1$	.270	51	50	$\bar{5}\,5\,1$	.484	81	85
$\bar{2}\,6\,1$	.300	109	109	$\bar{5}\,6\,1$	.501	14	19
$\bar{2}\,7\,1$	.331	65	72	$\bar{5}\,7\,1$	.520	8	13
$\bar{2}\,8\,1$	.364	4	12	$\bar{5}\,8\,1$	.542	6	5
$\bar{2}\,9\,1$	.398	117	95	$\bar{5}\,9\,1$	.566	57	48
$\bar{2}.10.1$	.433	79	68	$\bar{5}.10.1$	.591	44	45
$\bar{2}.11.1$	.469	16	15	$\bar{5}.11.1$	.617	49	49
$\bar{2}.12.1$	.505	—	0	$\bar{5}.12.1$	.645	—	6
$\bar{2}.13.1$	.541	56	46	$\bar{6}\,1\,1$	.533	46	55
$\bar{2}.14.1$	.577	69	69	$\bar{6}\,2\,1$	.536	17	27
$\bar{2}.15.1$	.615	36	40	$\bar{6}\,3\,1$	.544	—	4
$\bar{3}\,1\,1$	.272	31	32	$\bar{6}\,4\,1$	.554	—	2
$\bar{3}\,2\,1$	.280	86	81	$\bar{6}\,5\,1$	.566	—	8
$\bar{3}\,3\,1$	.294	35	30	$\bar{6}\,6\,1$	.581	46	45
$\bar{3}\,4\,1$	.311	11	20	$\bar{6}\,7\,1$	.597	22	25
$\bar{3}\,5\,1$	.333	5	7	$\bar{6}\,8\,1$	.602	—	6
$\bar{3}\,6\,1$	.357	59	55	$\bar{6}\,9\,1$	.637	28	29
$\bar{3}\,7\,1$	.384	24	22	$\bar{7}\,1\,1$	.621	40	46
$\bar{3}\,8\,1$	.413	22	20	$\bar{7}\,2\,1$	.625	19	20
$\bar{3}\,9\,1$	.443	43	35	$\bar{7}\,3\,1$	.631	10	18
$\bar{3}.10.1$	.474	44	44	$\bar{7}\,4\,1$	.639	—	3
$\bar{3}.11.1$	.507	—	11	$\bar{7}\,5\,1$	.650	21	21
$\bar{3}.12.1$	.541	4	6				

The structures described

The results of the two-dimensional Fourier synthesis, finally obtained after having improved the parameters by steps, are shown in Fig. 2 and Fig. 3. Fig. 2 is a projection of the electron densities of kröhnkite on (0 0 1) and Fig. 3 the same for brandtite. The corresponding positions of atoms are illustrated in Fig. 4, showing the structure of brandtite projected on (0 0 1). The structures

Table VI

Weissenberg photograph of Kröhnkite, monoclinic $CuNa_2(SO_4)_2 \cdot 2\,H_2O$. Rotation axis [001]. Zero layer line. Cu-K-radiation
Comparison between observed and calculated intensities.

h k l	$\frac{\sin\theta}{\lambda}$	$\|F\|$ obs.	$\|F\|$ calc.	*h k l*	$\frac{\sin\theta}{\lambda}$	$\|F\|$ obs.	$\|F\|$ calc.
1 0 0	0.091	29	33	3 2 0	0.285	36	40
2 0 0	.182	—	7	3 3 0	.298	80	72
3 0 0	.274	21	29	3 4 0	.316	60	50
4 0 0	.365	91	84	3 5 0	.338	5	4
5 0 0	.456	75	70	3 6 0	.363	31	40
6 0 0	.547	9	12	3 7 0	.390	36	33
7 0 0	.639	30	44	3 8 0	.420	—	0
0 2 0	.080	75	69	3 9 0	.450	32	38
0 4 0	.159	83	51	3.10.0	.483	14	14
0 6 0	.238	63	59	3.11.0	.516	23	26
0 8 0	.318	65	64	3.12.0	.550	33	45
0.10.0	.398	25	19	3.13.0	.585	15	28
0.12.0	.477	29	28	3.14.0	.620	11	21
0.14.0	.557	—	0	4 1 0	.367	5	9
0.16.0	.636	46	63	4 2 0	.373	53	49
1 1 0	.099	31	24	4 3 0	.383	27	24
1 2 0	.121	39	47	4 4 0	.398	6	12
1 3 0	.150	46	43	4 5 0	.415	6	5
1 4 0	.180	44	48	4 6 0	.436	23	24
1 5 0	.219	47	45	4 7 0	.458	10	8
1 6 0	.255	47	37	4 8 0	.484	26	30
1 7 0	.293	9	17	4 9 0	.511	16	26
1 8 0	.331	28	30	4.10.0	.539	18	17
1 9 0	.370	—	0	4.11.0	.570	3	1
1.10.0	.408	14	21	4.12.0	.601	—	4
1.11.0	.446	18	16	4.13.0	.632	11	12
1.12.0	.485	36	46	5 1 0	.457	33	24
1.13.0	.525	—	4	5 2 0	.463	15	12
1.14.0	.564	11	27	5 3 0	.471	24	25
1.15.0	.603	28	35	5 4 0	.483	—	10
1.16.0	.642	—	5	5 5 0	.497	—	2
2 1 0	.187	10	9	5 6 0	.515	37	39
2 2 0	.199	22	16	5 7 0	.534	—	1
2 3 0	.218	13	13	5 8 0	.556	38	49
2 4 0	.242	52	45	5 9 0	.579	—	5
2 5 0	.269	4	11	5.10.0	.605	24	32
2 6 0	.300	65	74	5.11.0	.632	2	14
2 7 0	.332	19	29	6 1 0	.548	5	6
2 8 0	.366	—	5	6 2 0	552	11	14
2 9 0	.402	10	13	6 3 0	.560	13	16
2.10.0	.438	34	35	6 4 0	.570	38	40
2.11.0	.474	18	10	6 5 0	.581	6	18
2.12.0	.511	54	68	6 6 0	.596	31	35
2.13.0	.551	—	4	6 7 0	.613	14	25
2.14.0	.585	21	36	6 8 0	.633	5	11
2.15.0	.623	—	1	7 1 0	.639	10	19
3 1 0	.276	40	35				

Table VII

Weissenberg photograph of Kröhnkite, monoclinic $CuNa_2(SO_4)_2 \cdot 2\,H_2O$. Rotation axis [001]. First layer line. Cu-K-radiation.
Comparison between observed and calculated intensities.

h k l	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.	*h k l*	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.
0 1 1	0.104	9	22	2.12.1	0.529	—	5
0 2 1	.125	—	2	2.13.1	.565	3	10
0 3 1	.153	100	65	2.14.1	.602	8	11
0 4 1	.186	4	6	3 1 1	.318	34	32
0 5 1	.221	28	32	3 2 1	.325	16	27
0 6 1	.257	17	23	3 3 1	.337	35	31
0 7 1	.294	45	34	3 4 1	.353	6	13
0 8 1	.332	9	6	3 5 1	.372	25	33
0 9 1	.370	22	32	3 6 1	.395	35	31
0.10.1	.409	16	11	3 7 1	.420	22	25
0.11.1	.448	11	19	3 8 1	.448	—	7
0.12.1	.487	—	13	3 9 1	.477	33	37
0.13.1	.526	44	47	3.10.1	.507	24	24
0.14.1	.565	—	2	3.11.1	.539	14	28
0.15.1	.604	22	34	3 12.1	.572	8	7
0.16.1	.644	—	9	4 1 1	.405	7	19
1 1 1	.156	58	68	4 2 1	.411	19	7
1 2 1	.170	90	86	4 3 1	.420	65	79
1 3 1	.192	26	36	4 4 1	.433	—	13
1 4 1	.219	—	9	4 5 1	.449	46	58
1 5 1	.249	25	32	4 6 1	.468	—	3
1 6 1	.282	80	72	4 7 1	.490	6	3
1 7 1	.316	25	29	4 8 1	.512	6	3
1 8 1	.352	—	5	4 9 1	.539	7	2
1 9 1	.388	47	49	4.10.1	.566	6	3
1.10.1	.425	62	57	4.11.1	.595	18	37
1.11.1	.463	19	25	5 1 1	.494	22	38
1.12.1	.500	14	5	5 2 1	.499	18	18
1.13.1	.538	6	4	5 3 1	.507	13	20
1.14.1	.577	30	39	5 4 1	.517	9	1
1.15.1	.615	30	33	5 5 1	.531	5	11
2 1 1	.233	22	28	5 6 1	.547	14	14
2 2 1	.242	18	22	5 7 1	.566	26	31
2 3 1	.258	66	80	5 8 1	.586	10	10
2 4 1	.279	20	13	5 9 1	.609	30	16
2 5 1	.308	3	7	5.10.1	.633	13	5
2 6 1	.331	16	11	6 1 1	.583	40	41
2 7 1	.361	32	23	6 2 1	.588	15	10
2 8 1	.392	9	2	6 3 1	.594	3	13
2 9 1	.425	56	56	6 4 1	.603	11	5
2.10.1	.459	—	11	6 5 1	.615	2	3
2.11.1	.494	16	19	6 6 1	.629	15	21

proposed are further shown by a projection of kröhnkite on (1 0 0). Fig. 5. From Fig. 5 it is seen that each S (As) atom is in the middle of an almost regular tetrahedron, formed by oxygen atoms. The average distances S-O in the SO_4 tetrahedron, 1.48 Å, and As-O in the AsO_4 tetrahedron, 1.67 Å, are in good agreement with those found in other structures. In comparison can be

Table VII (cont).

h k l	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.	*h k l*	$\frac{\sin\theta}{\lambda}$	|F| obs.	|F| calc.
$\bar{1}$ 1 1	0.119	18	17	$\bar{3}$.13.1	0.580	16	16
1 2 1	.137	54	44	$\bar{3}$.14.1	.615	13	14
1 3 1	.164	65	77	$\bar{4}$ 1 1	.352	5	20
1 4 1	.195	5	12	$\bar{4}$ 2 1	.359	57	48
1 5 1	.228	68	61	$\bar{4}$ 3 1	.370	47	33
$\bar{1}$ 6 1	.263	—	2	$\bar{4}$ 4 1	.384	—	2
$\bar{1}$ 7 1	.300	31	15	$\bar{4}$ 5 1	.402	46	39
1 8 1	.337	7	4	$\bar{4}$ 6 1	.423	25	10
1 9 1	.375	29	23	$\bar{4}$ 7 1	.447	22	22
$\bar{1}$.10.1	.413	16	10	$\bar{4}$ 8 1	.473	5	6
$\bar{1}$.11.1	.451	24	34	$\bar{4}$ 9 1	.500	28	27
1.12.1	.490	14	16	$\bar{4}$.10.1	.529	19	28
1.13.1	.529	22	35	$\bar{4}$.11.1	.560	27	28
$\bar{1}$.14.1	.568	16	16	$\bar{4}$.12.1	.592	—	11
$\bar{1}$.15.1	.607	19	26	$\bar{4}$.13.1	.624	32	22
2 1 1	.185	77	74	$\bar{5}$ 1 1	.440	—	12
$\bar{2}$ 2 1	.197	52	49	$\bar{5}$ 2 1	.446	54	26
$\bar{2}$ 3 1	.216	37	36	$\bar{5}$ 3 1	.454	70	67
$\bar{2}$ 4 1	.241	20	21	$\bar{5}$ 4 1	.466	15	4
$\bar{2}$ 5 1	.268	23	9	$\bar{5}$ 5 1	.482	43	41
$\bar{2}$ 6 1	.299	57	57	$\bar{5}$ 6 1	.499	6	12
$\bar{2}$ 7 1	.332	51	45	$\bar{5}$ 7 1	.519	13	10
2 8 1	.366	—	3	$\bar{5}$ 8 1	.542	3	3
$\bar{2}$ 9 1	.401	69	69	$\bar{5}$ 9 1	.566	3	12
2.10.1	.437	21	43	$\bar{5}$.10.1	.592	16	15
$\bar{2}$.11.1	.473	7	8	$\bar{5}$.11.1	.619	14	22
$\bar{2}$.12.1	.509	10	4	$\bar{5}$.12.1	.648	—	8
$\bar{2}$.13.1	.547	12	8	$\bar{6}$ 1 1	.529	64	45
2.14.1	.585	18	21	$\bar{6}$ 2 1	.534	—	12
$\bar{2}$.15.1	.623	27	37	$\bar{6}$ 3 1	.541	12	11
3 1 1	.266	13	13	$\bar{6}$ 4 1	.551	—	0
$\bar{3}$ 2 1	.275	33	20	$\bar{6}$ 5 1	.564	—	10
3 3 1	.289	76	77	$\bar{6}$ 6 1	.579	6	9
3 4 1	.307	45	23	6 7 1	.597	23	30
$\bar{3}$ 5 1	.330	34	26	$\bar{6}$ 8 1	.609	8	7
$\bar{3}$ 6 1	.355	23	15	$\bar{6}$ 9 1	.638	31	39
$\bar{3}$ 7 1	.383	—	10	$\bar{7}$ 1 1	.619	40	34
$\bar{3}$ 8 1	.413	—	6	$\bar{7}$ 2 1	.623	9	6
$\bar{3}$ 9 1	.444	31	42	$\bar{7}$ 3 1	.630	11	9
$\bar{3}$.10.1	.477	31	28	$\bar{7}$ 4 1	.638	11	10
3.11.1	.510	31	32	$\bar{7}$ 5 1	.649	20	6
$\bar{3}$.12.1	.545	—	0				

mentioned the following distances As-O found by other investigators. H. MORI and T. ITO (1950) in symplesite, $Fe(AsO_4) \cdot 8\,H_2O$, 1.60, 1.63, 1.69 Å; MOONEY (1948) in $BiAsO_4$, 1.63 Å; BUBECK and MACHATSCHKI (1935) in berzeliite 1.68 ± ± 0.04 Å; MACHATSCHKI (1935) in $AlAsO_4$ 1.68 Å; SCHULTZE (1934) in $BAsO_4$ 1.66 Å; P. KOKKOROS (1938) in durangite 1.68 Å; H. HERITSCH (1938) in olivenite 1.49, 1.45 and 1.81 Å.

The value 1.63 Å found by MOONEY is independent of parameter determination, and obtained by comparison of the cell volumes of the arsenates $AlAsO_4$

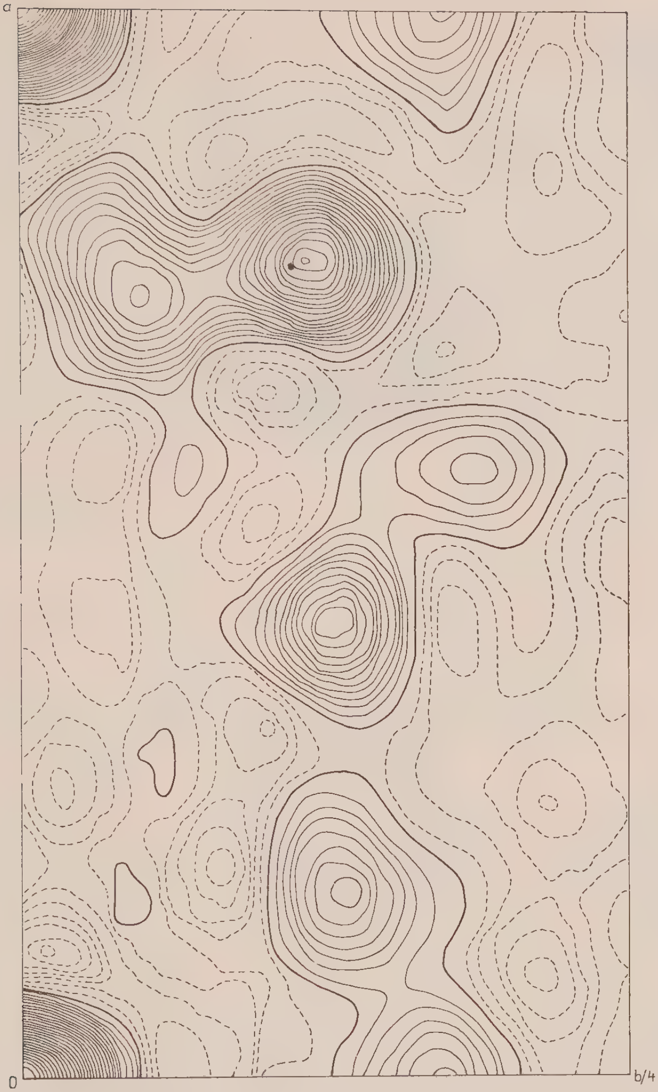

Fig. 2. Two-dimensional Fourier synthesis. The electron densities of kröhnkite projected on (0 0 1).

and $BAsO_4$ with respect to the isomorphous phosphates $AlPO_4$ and BPO_4. MOONEY found that the arsenate group was about 3.5 % larger than the phosphate group. Since the distance P-O in the phosphate group has been accurately determined as 1.56 Å, the distance As-O in the arsenate group was taken to be 1.63 Å. The values 1.45 Å and 1.49 Å found by HERITSCH must be too short and his value 1.81 Å too large. RICHMOND (1940) has also shown that the space group

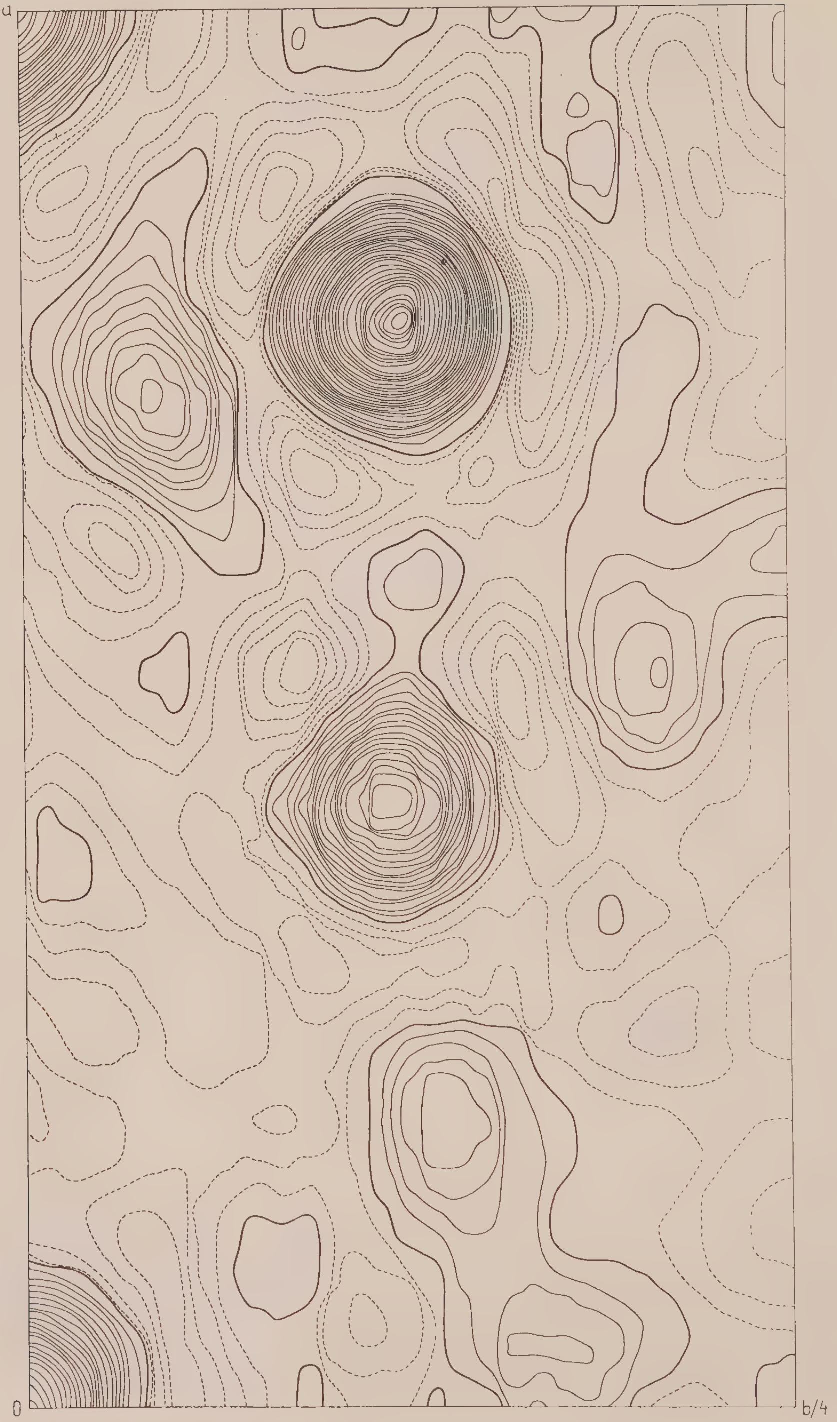

Fig. 3. Two-dimensional Fourier syntesis. The electron densities of brandtite projected on (0 0 1).

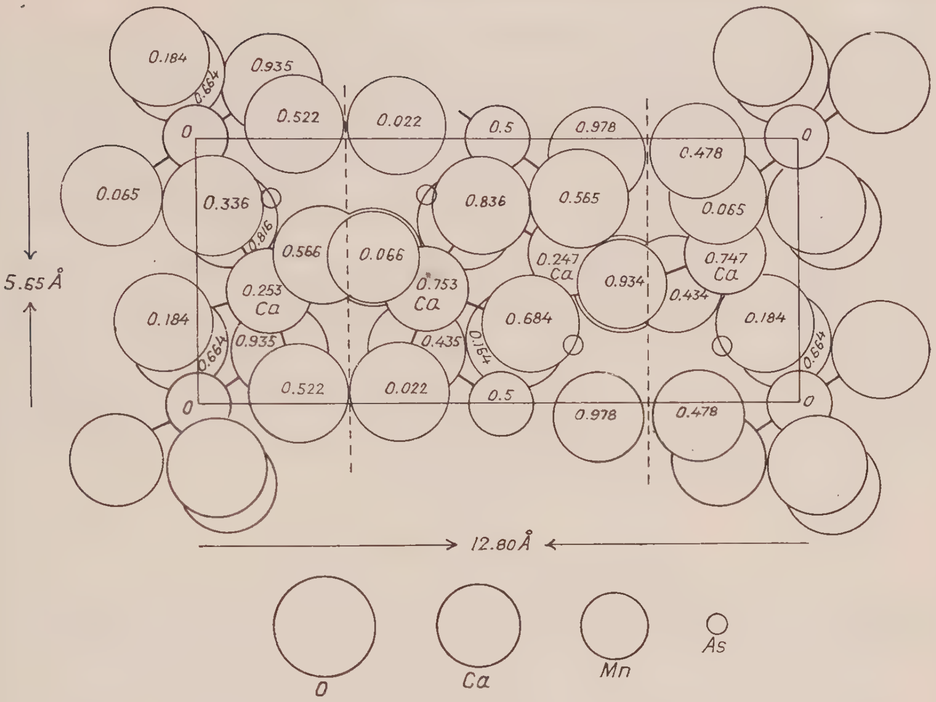

Fig. 4. The structure of brandtite projected on (0 0 1).

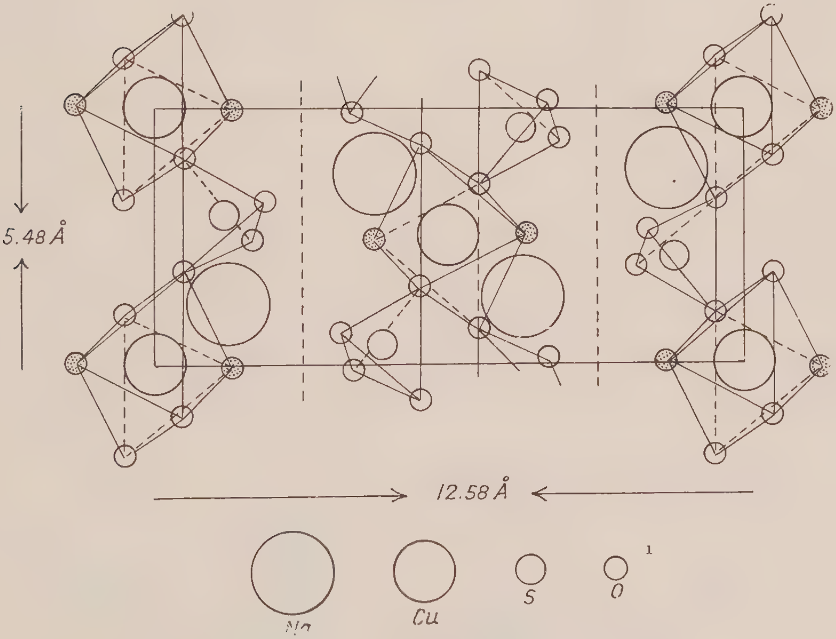

Fig. 5. The structure of kröhnkite projected on (1 0 0).

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[1] Small circles filled with dots represent water molecules.

D_{2h}^{12} proposed by HERITSCH for olivinite is in error. The true space group according to RICHMOND is D_2^4.

The manganese (copper) atom occupies the centre of an octahedron formed by four oxygen atoms and two water groups. Each Mn(Cu) octahedron has one oxygen atom in common with four different arsenate (sulphate) tetrahedra. Thus the crystals are built up by infinite chains of $Mn(AsO_4)_2 \cdot 2\,H_2O$ respectively $Cu(SO_4)_2 \cdot 2\,H_2O$ parallel to the *c*-axes, and passing through the edges and the middle of the unit cell.

The calcium (sodium) atoms occupy the interstices left vacant by the chains and are each surrounded by six oxygen atoms and one water molecule. Two oxygen atoms and one H_2O group are shared with one chain, three oxygen atoms are in common with the adjacent chain in the *a*-direction, and only one oxygen atom is in common with the adjacent chain in the *b*-direction. The distances Ca-O and Na-O found (see Table VIII) are in good agreement with those found in other structures, and with those obtained from the sum of the radii of the metal and oxygen atoms.

Table VIII

Interatomic distances in brandtite

Atom	Co-ordination	Number of atoms	Kinds of atoms	Distance (Å)
Mn	6	1.1	O_{II}, $\overset{*}{O}_{II}$	2.27, 2.27
	octahedron	1.1	O_{III}, O_{III}	2.19, 2.19
		1.1	H_2O, H_2O	2.11, 2.11
As	4	1	O_I	1.61
	tetrahedron	1	O_{II}	1.65
		1	O_{III}	1.76
		1	O_{IV}	1.65
Ca	7	1	O_I	2.48
		1.1	$\overset{*}{O}_{II}$, $\overset{*}{O}_{II}$	2.80, 2.36
		1	O_{III}	2.30
		1.1	O_{IV}, O_{IV}'	2.32, 2.50
		1	H_2O	2.36
Mn			Ca	3.38
Mn			As	3.33, 3.60
Ca			As	2.86
Distances O—O in the manganese octahedron.				
O_{II}			O_{III}, O_{III}	3.04, 3.27
			H_2O, H_2O	2.92, 3.26
O_{III}			H_2O, H_2O	2.62, 3.41

Dashes denote equivalent atoms and asterisks atoms in adjacent cells.

Table VIII (cont.)

Interatomic distances in kröhnkite

Atom	Co-ordination	Number of atoms	Kinds of atoms	Distance (Å)
Cu	6	1.1	O_{II}, O^*_{II}	2.23, 2.23
	octahedron	1.1	O_{III}, O_{III}	2.17, 2.17
		1.1	H_2O, H_2O	1.92, 1.92
S	4	1	O_I	1.42
	tetrahedron	1	O_{II}	1.46
		1	O_{III}	1.54
		1	O_{IV}	1.50
Na	7	1	O_I	2.46
		1.1	O^*_{II}, O^*_{II}	2.66, 2.44
		1	O_{III}	2.30
		1.1	O_{IV}, O_{IV}'	2.61, 2.33
		1	H_2O	2.31
Cu			S	3.37
			Na	3.51
Na			S	3.11
Distances O—O in the copper octahedron.				
O_{II}			O_{III}, O_{III}	3.04, 3.17
			H_2O, H_2O	2.67, 3.18
O_{III}			H_2O, H_2O	2.89, 2.89

Dashes denote equivalent atoms and asterisks atoms in adjacent cells.

Each water molecule is bound to one Mn(Cu) atom and one Ca(Na) atom. The bond angle Mn-H_2O-Ca in brandtite is found to be 98°.1, and the angle Cu-H_2O-Na in kröhnkite 111°.8, which is very close to the tetrahedral angle 112°.4. The distance Mn-H_2O and Cu-H_2O are 2.11 Å and 1.92 Å corresponding to a very short metal-oxygen distance. This is easily understood from the fact that $Mn^{2\cdot}$ and $Cu^{2\cdot}$ ions have fairly strong polarization powers. The distances Ca-H_2O and Na-H_2O are found to be 2.36 Å and 2.31 Å respectively and are in good agreement with those found in other structures. The water molecules in brandtite and kröhnkite are further bound to the following oxygen atoms:

Mineral	Oxygen atom	Distance O-H_2O	Bond angle
Brandtite	O_I	2.66 Å	92°.7
	O_{III}	2.62 Å	111°.7
	O_{IV}	2.78 Å	102°.8
Kröhnkite	O_I	2.61 Å	94°.3
	O_{IV}	2.63 Å	89°.7
	O_{II}	2.67 Å	

JENSEN (1948) in his review on salt hydrates gave the following rules for the co-ordinated water molecules of cystals: "A water molecule has always negative neighbours on one side, positive neighbours on the opposite side. A water molecule touches one or two positive neighbours on one side, almost always two negative neighbours on the opposite side. If the water molecules have two positive neighbours the bond angle between them and the water molecules must be about 112°.4. This bond angle is a very characteristic feature according to JENSEN, and consequently he rejected the structures proposed for TUTTON's salts and for $LiCl \cdot H_2O$, where the water molecules are placed on the lines connecting two cations. He further made the statement that structural suggestions, in which the environment of the water molecules does not show its positive and negative side, may be discarded as false. Structures in which the water molecules have more than two positive neighbours may be considered as very improbable. Structural suggestions, in which the water molecules have more than two negative neighbours must be firmly founded in order to be accepted. LINDQVIST (1948) proves that JENSEN'S statements are very well founded on the crystal structures considered by JENSEN, but that he has drawn his conclusion too far. The structure of $(NH_4)_2FeCl_5H_2O$ proposed by LINDQVIST (1946) does not indicate one positive and one negative side of the water molecule which furthermore has more than two positive and two negative neighbours. As to the last statement, that a water molecule only has two neighbours, JENSEN himself pointed out a few exceptions, among them the structure of $SrCl_2 \cdot 2\,H_2O$ proposed by himself. In the structure of brandtite and kröhnkite treated in this paper, the water molecules have two positive neighbours with almost tetrahedral bond angles to water, but more than two negative neighbours. The distances H_2O-O found, are perhaps not quite correct on account of the inaccuracy of the oxygen and water parameters, particularly the corresponding z parameters, but the tendency for the water molecules to have more than two negative neighbours is beyond dispute.

Perhaps JENSEN'S statement is correct for a water molecule in a co-ordination polyhedron built up completely of water molecules, but it is hardly a general rule for a water molecule in a polyhedron built up of water molecules together with anions.

JENSEN further made the statement that PAULING's principle is not valid in structures of salt hydrates. This may be true, but PAULING's principle must always be considered at least as a very rough approximation, while a greater departure from this principle must always be regarded as suspicious. It is true that in a salt hydrate in which water molecules distribute charges between cations and anions, it is impossible to draw any conclusion on the distribution of charges without knowing the exact parameters, and thus without the possibility of determining the "bond strength". It is also quite correct that the PAULING diagram for $NiSO_4 \cdot 7\,H_2O$ made by BEEVERS and SCHWARTZ is too idealized, but an application of PAULING's principle even to salt hydrates may give a proof of the reliability of a proposed structure. The present author has tried to use PAULING's principle on brandtite and kröhnkite, and as a very rough approximation found the following:

In brandtite:

O_{I} 1 Ca, 1 As, 1 Mn by means of H_2O	$2/7 + 5/4 + 2/6 = 1.87$
O_{II} 2 Ca, 1 As, 1 Mn	$4/7 + 5/4 + 2/6 = 2.20$
O_{III} 1 Ca, 1 As, 1 Mn, 1 Ca by means of H_2O	$2/7 + 5/4 + 2/6 + 1/7 = 2.06$
O_{IV} 2 Ca, 1 As, 1 Ca by means of H_2O	$4/7 + 5/4 + 1/7 = 1.96$

In kröhnkite:

O_{I} 1 Na, 1 S, 1 Cu by means of H_2O	$1/7 + 6/4 + 2/6 = 1.98$
O_{II} 2 Na, 1 S, 1 Cu	$2/7 + 6/4 + 2/6 = 2.12$
O_{III} 1 Na, 1 S, 1 Cu	$1/7 + 6/4 + 2/6 = 1.98$
O_{IV} 2 Na, 1 S, 1 Na by means of H_2O	$2/7 + 6/4 + 1/7 = 1.93$

In kröhnkite a short distance between O_{II} and H_2O is found. This cannot be explained as dependent on a distribution of charge between O_{II} and a cation through an intermediate water molecule, but only shows the uncertainty in the application of PAULING's principle given above.

Morphological and physical properties explained by the structures

As pointed out by earlier investigators, crystals of brandtite and kröhnkite often are grown prismatic elongated parallel to the *c*-axis. In the description of the structures the present writer pointed out that crystals of the minerals are built up by chains of $M^{II}(XO_4)_2 \cdot 2\,H_2O$ groups stretched indefinitely in the direction of the *c*-axis. This structural feature of the two minerals easily explains the pronounced tendency of their crystals to be elongated parallel to that direction. The forces holding separate chains together are strong in the direction of the *a*- and *c*-axis, but very weak in the direction of the *b*-axis in which there is only one feeble Ca(Na)-O bond. This zone of weakness in the crystal (marked out by pointed lines in Fig. 4 and Fig. 5), perfectly explains the distinct cleavage parallel to (0 1 0) earlier found. PALACHE in crystals of kröhnkite found another cleavage parallel to $(\bar{1}\,0\,1)$ characterized as very imperfect. No structural explanation for such a cleavage is found.

The relation between kröhnkite and the $A_3(XO_4)_2 \cdot 2\,H_2O$ compounds

The structures of kröhnkite and brandtite found, confirmed the authors assumption that the two minerals are isostructural. The cell volume of kröhnkite 378 Å^3, is smaller than that of brandtite 403 Å^3, in keeping with the fact that all atoms and groups in kröhnkite have smaller dimensions than the corresponding elements in brandtite.

GEIGER (1948) described species of brandtite found in Falotta in Oberhalbstein, containing about 3 per cent of magnesium. It is a well-known fact, found in several minerals, that manganese can be isomorphically replaced by magnesium. Disregarding the false cell dimensions given by GEIGER, the descriptions of the Falotta species are very close to that of brandtite given by AMINOFF and later by WOLFE. The birefringence 0.016 and the calculated specific gravity 3.65 of the brandtite from Falotta are smaller than the corresponding values 0.020 and 3.70 of Mn-brandtite, and easily explained by the differences in composition. The magnesium in the Falotta brandtite tends to lower the index of refraction and the specific gravity.

As already mentioned in the introduction, WOLFE found that roselite is isostructural with brandtite. The smaller cell volume found in roselite is in good agreement with the smaller size of the cobalt ion compared with the maganese ion. Thus in roselite the crystals may be built up by chains of (Co, Mg) $(AsO_4)_2 \cdot 2\,H_2O$ groups stretched indefinitely in the direction of the *c*-axis. Considering the close relation between the arsenate ion and the phosphate ion, it could be expected that brandtite, roselite and the corresponding phosphates should be isostructural. Crystals of fairfieldite $(Mn, Fe)Ca_2(PO_4)_2 \cdot 2\,H_2O$, in which manganese is only to a small extent replaced by iron, have, however, triclinic symmetry. WOLFE (1940) described fairfieldite (see Table I in this paper), and found that the unit-cell of the mineral contains only one molecule, but is simply related to that of brandtite, *a* and *c* being practically the same, while *b* is doubled in brandtite. He also determined the space group of fairfieldite and found it to be $C_i^1 - P\,\bar{1}$. There is no doubt that the minerals are closely related, and that the higher symmetry can be obtained from the lower by twinning of the lattice, a single plane of reflexion producing monoclinic symmetry with a doubled cell volume. Assuming that crystals of fairfieldite are built up by chains of $(Mn, Fe)_2(PO_4) \cdot 2\,H_2O$ groups, it can be expected that manganese can be isomorphically replaced by iron. The lower symmetry of fairfieldite must be caused by the phosphate groups, the slightly smaller volume (3.5 %) of which lowers the symmetry by deforming the structure. If crystals of fairfieldite are built up by infinite chains parallel to the *c*-axes, and the chains are analogous to those in brandtite, the only difference being that the arsenate groups are replaced by the 3.5 per cent smaller phosphate groups, there must be a simple relation between the *c*-axes of the two minerals. From Table I it is seen that the *c*-axis of brandtite is 3.2 per cent larger than that of fairfieldite, in good agreement with the relation between the volumes of the arsenate and phosphate ions.

The foregoing suggests that the crystal of the triclinic members of the $A_3(XO_4)_2 \cdot 2\,H_2O$ family may be built up by infinite chains $M(PO_4)_2 \cdot 2\,H_2O$ parallel to the *c*-axes, and their structures may be closely related to those of the monoclinic members. The higher symmetry of the monoclinic members can be obtained directly from the lower by twinning of the lattice.

The structural relationship to Tutton's salts

In the introduction the present writer pointed out that the crystal structures of kröhnkite and brandtite might be closely related to those of TUTTON's salts. The crystal structures of TUTTON's salts as given by HOFMANN are certainly not quite correct, and a reinvestigation needs to be done, but probably only of the oxygen and water parameters. The parameters of the metal atoms are certainly correct but the light atoms, placed only according to geometrical reasons and their parameters not checked against estimated intensities, may be slightly modified. In the main, however, the structures proposed by HOFMANN are correct and the structure of picromerite $MgK_2(SO_4)_2 \cdot 6\,H_2O$ is shown projected on (1 0 0) in Fig. 6.

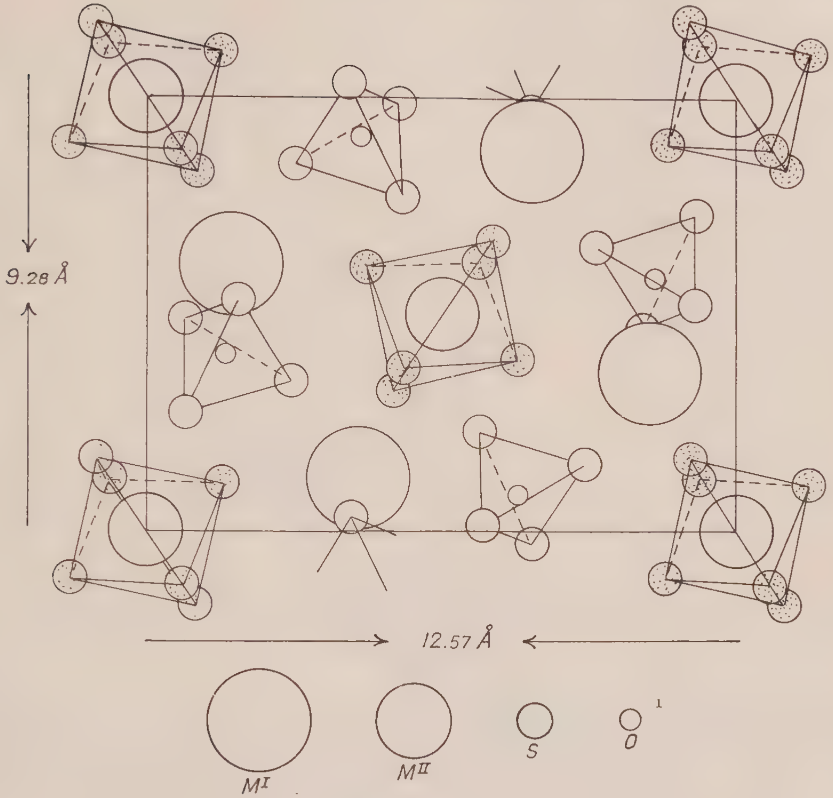

Fig. 6. The structure of $Mg(NH_4)_2(SO_4)_2 \cdot 6\,H_2O$, projected on (1 0 0).

From Fig. 6 it is seen that the crystal of picromerite is built up by complexes of magnesium water octahedra and tetrahedral sulphate groups held together only by weak water-oxygen bonds. The potassium atoms occupy the interstices left vacant by the complexes. There are no strong infinite chains in the crystals as in kröhnkite, a fact which explains the pronounced cleavage parallel to (2 0 1) and running through the weak oxygen-water bond mentioned above. A comparison between Fig. 5 and Fig. 6 in this paper shows the close relation between the structures of kröhnkite and TUTTON's salts. In TUTTON's salts the six water molecules build up an octahedron round the divalent metal ion and thus form a hexaquo ion. In kröhnkite in which there are only two water molecules, the unit cells are pressed together essentially in the direction of the *c*-axis, and the octahedral co-ordination round the divalent cation is built up by means of two water molecules and four oxygen atoms from the sulphate tetrahedra. A comparison between kröhnkite and another TUTTON's salt cyanochroite $CuK_2(SO_4)_2 \cdot 6\,H_2O$ which contains the same divalent cation and the same radical $(SO_4)^{2-}$ as kröhnkite shows an interesting relation between the two salt hydrates. If potassium in cyanochroite is replaced by sodium the hexahydrated salt becomes unstable and the dihydrated sodium salt kröhnkite is formed, with a

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[1] Small circles filled with dots represent water molecules.

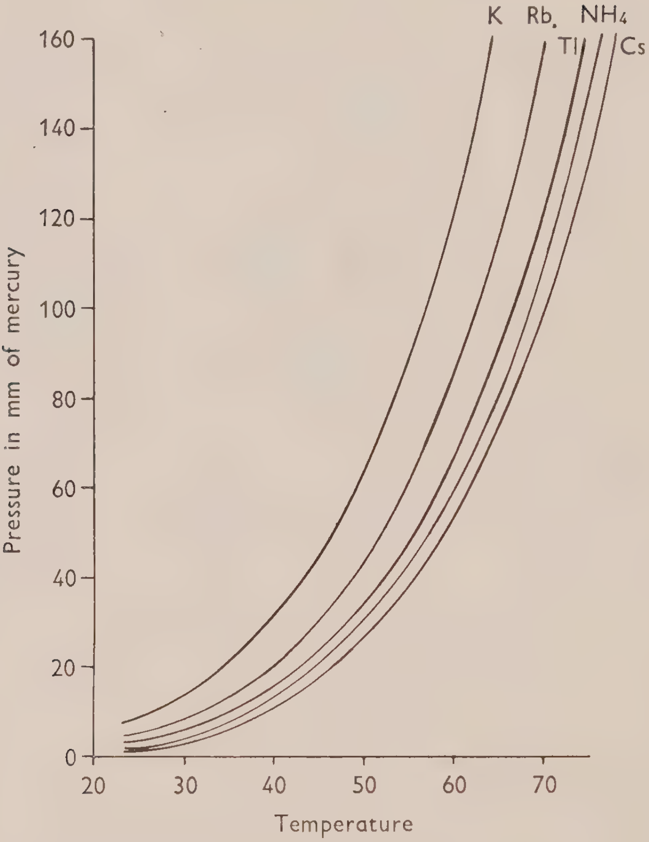

Fig. 7. Vapour pressure curves for compounds $M_2^I M^{II}(SO_4)_2 \cdot 6\,H_2O$. The bivalent metals are Cu, Cd and Mn.

closely related structure. Too little is known about the crystal chemistry of salt hydrates to draw any further conclusions, but a few facts are worth mentioning about the stability of Tutton's salts and the corresponding tetra and dihydrates.

Caven and Ferguson (1922) made an investigation to discover whether the aqueous vapour pressures of hydrated double sulphates became modified by exchanging one alkali metal for another in the known copper type of Tutton's salts, and also by substituting another bivalent metal for copper while the same alkali metal was retained. They also made an attempt to prepare the hexahydrate of Na, but with negative result.

The results of their investigation on $M_2'Cu(SO_4)_2 \cdot 6\,H_2O$ are shown in Fig. 7. The vapour pressure is less; that is the water of crystallization is held more firmly, the greater the electropositiveness of the alkali in the double salt.

Substituting the bivalent metal in the different alkali double salts, they found that in general the same sequence appeared, but not with the hexahydrated Cs double salts.

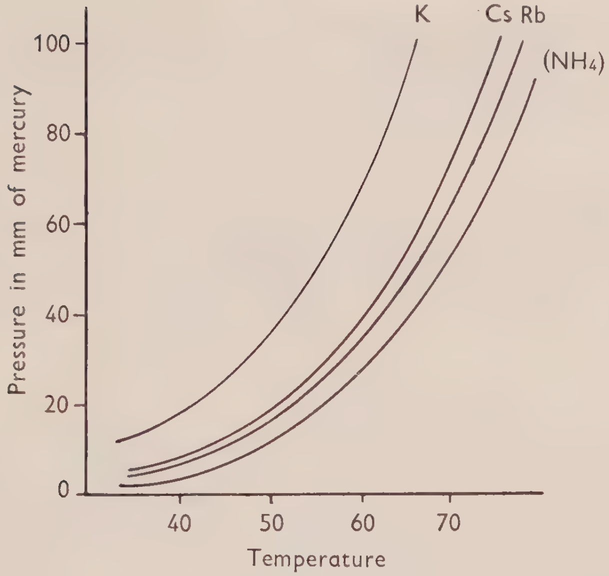

Fig. 8. Vapour pressure curves for compounds $M_2^IM^{II}(SO_4)_2 \cdot 6\,H_2O$. The bivalent metals are Co, Ni, Zn, Fe and Mg.

In the case of the bivalent metals Cu, Mn and Cd, which do not form heptahydrated sulphates stable at ordinary temperature, the aqueous vapour pressure of the double salts formed with different alkali metals decreases with the alkali metal in the same order as given above.

In the case of the bivalent metals Co, Ni, Zn, Fe, and Mg which form stable heptahydrates however, the order is K · Cs, Rb. The result is illustrated in Fig. 8 showing the vapour pressure curves for $M_2'Zn(SO_4)_2 \cdot 6\,H_2O$.

Ferguson (1925) made a corresponding investigation on the double selenates and found that, at the same temperature, the aqueous vapor pressures of the double selenates are higher than those of the corresponding sulphates.

As a summary of these investigations it can be stated that the stabilities of the hexahydrated double salts are greatly influenced by the molecular and atomic volumes of the groups and atoms of the molecules. The specific action of the different atoms and groups introduces irregularities, especially noticeable in the case of Cs double salts, but in general the stabilities of the hydrates increase with increasing volume of the univalent cation and decrease with increasing volume of the divalent cation and the anion. From this it can be deduced that the potassium double salts are the least stable as hexahydrates, and especially when combined with large divalent cation. In good agreement with this Ferguson found that the double sulphates of manganese or cadmium with potassium could not be prepared as hexahydrates.

Federoff and Demassieux (1941) made a thorough investigation of the double potassium sulphates with Cd, Mn, Fe, Mg, Cu, Zn, Co, and Ni. Their results, together with small additions, such as those concerning the tetrahydrated Cd, double sulphates, are shown in Fig. 9.

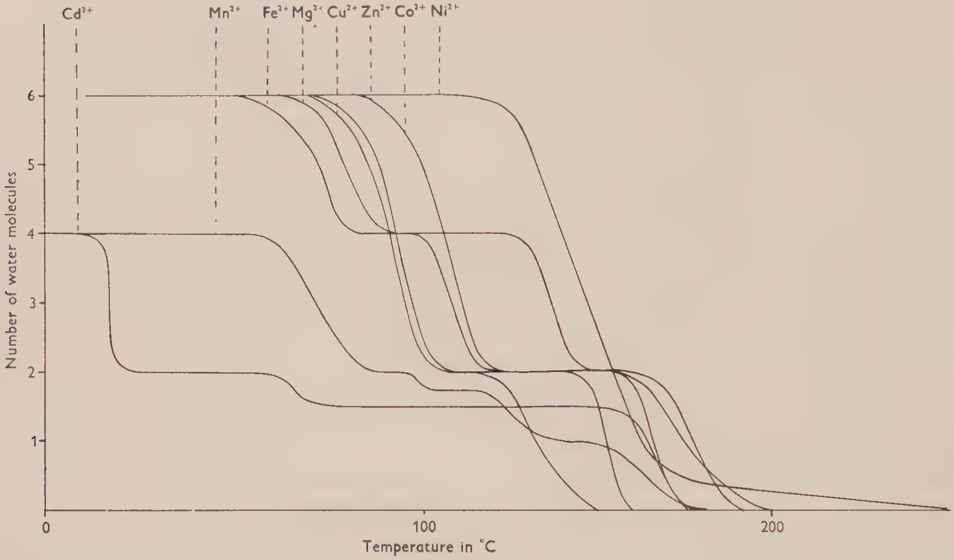

Fig. 9. Dehydration curves for compounds $K_2^I M^{II} (SO_4)_2 \cdot nH_2O$. After B. Federoff (1941).

From Fig. 9 it is seen that the stability of the hexahydrates increases with increasing volume of the divalent cation, but Mg shows a marked exception. Tetrahydrates are formed with Cd, Mn, Fe and Mg. According to WYROUBOFF (1891) the tetrahydrate of the Cd double salts is stable only between 0° -16° C and decomposes easily in air, giving off two molecules of water. Crystals of Mg double salt leonite are found in the salt deposits of Leopoldshall. ANSPACH (1939), in his work on $MnK_2(SO_4)_2 \cdot 4\,H_2O$, called Mn-leonite by him, proposed a structure of the salt. The lattice constants of Mn-leonite determined by ANSPACH are in good agreement with those of leonite found by earlier investigators. The space group is $C_{2h}^3 - P\,2/m$. The unit cells contain four molecules. According to ANSPACH the structure is built up by sulphate tetrahedra and $Mn(H_2O)_4^{2+}$-complexes. Manganese is surrounded by four water molecules, situated in the corner of a square. Four co-ordination of Mn^{2+} with respect to water molecules has been found earlier, but according to ANSPACH Mn-leonite is isomorphous with leonite and consequently four co-ordination of water round Mg in leonite should be expected. Such a water co-ordination round the Mg^{2+} is very improbable. Several facts indicate that the structure of Mn-leonite proposed is not quite correct and perhaps the orientation of sulphate tetrahedra can be changed to incorporate octahedral co-ordination of two sulphate oxygen and four water molecules round the Mg^{2+} ions. ANSPACH gives two distances K-O to be 2.38 Å and 2.28 Å and furthermore a comparison of F_{obs} and F_{calc} shows several large departures between them, which indicate that the water and oxygen parameters can be changed to a certain degree. No hexahydrated $Na_2M''(SO_4)_2$ compounds are found, showing that the volume of Na is too small to permit stable hexahydrates. A tetrahydrate astrakanite $Na_2Mg(SO_4)_2 \cdot 4\,H_2O$ is known and two dihydrates, namely, the mineral kröhnkite described in this paper and loewite

$Na_2Mg(SO_4)_2 \cdot 2\,H_2O$. Very little is known about loewite. STRUNZ in his Mineralogical Tables describes the mineral as tetragonal but points out that this description is very doubtful. Perhaps loewite is monoclinic and isostructural with kröhnkite.

Acknowledgements

This investigation has been carried out at the Mineralogical Department of the Swedish Museum of Natural History, the collection of minerals and the equipment of which were kindly placed at my disposal by Professor FRANS E. WICKMAN. I also wish to thank Professor WICKMAN for many valuable discussions in the course of the investigation.

SUMMARY

The structure of brandtite $MnCa_2(AsO_4)_2 \cdot 2\,H_2O$, and kröhnkite $CuNa_2(SO_4)_2 \cdot 2\,H_2O$ have been investigated. The symmetries of the two minerals are monoclinic, and the cell dimensions (see Table I) earlier found by WOLFE and RICHMOND have been found to be correct. The space groups are $C_{2h}^5 - P\,2_1/c$. The parameters are found by the method of trial and error, and the parameter corrections are controlled by Fourier synthesis. The final parameters are given in Table III.

The two minerals are found to be isostructural with one another and with roselite. The divalent metals occupy the centres of octahedra formed by four oxygen atoms and two water molecules. Tetrahedral co-ordination of oxygen round arsenic and sulphur is found. Each M^{II}-octahedron has one oxygen atom in common with four different AsO_4 or SO_4 tetrahedra. Thus the crystals are built up by infinite chains of $M^{II}(XO_4)_2 \cdot 2\,H_2O$ groups parallel to the c-axes running through the edges and the middle of the unit cells. The univalent metals occupy the interstices left vacant by the chains, and are surrounded by six oxygen atoms and one water molecule. The water molecules have two positive neighbours on one side and three negative neighbours on the opposite side. The interatomic distances found (see Table VIII) are in good agreement with those found in other structures. Morphological properties and cleavages are explained by the structures. The structures of the two minerals have been found to be closely related to those of TUTTON's salt. The structural relations to fairfieldite and collinsite are discussed. Some fact on salt hydrates are mentioned.

Riksmuseets Mineralogiska Avdelning, Stockholm 50 and Stockholms Högskolas Mineralogiska Institution, Stockholm, March 1951.

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The distribution of barium and strontium in the rocks and minerals of the syenitic and alkaline rocks of Alnö Island

By Harry von Eckermann

With 1 figure in the text

A memoir on the rocks of the alkaline district of Alnö and their genesis was published by the author of the present article, in the year 1948 (1). In the same year a preliminary contribution was made to the knowledge of the distribution of barium in these rocks, at the 18th session of the International Geological Congress (2). Since then the rockforming minerals of the district have been subjected to continued research work, and special attention was paid to the Ba and Sr contents. Supplementary determinations of the contents of the corresponding rocks were made simultaneously.

A final report is now offered on the distribution of barium and strontium in the rockminerals as well as in the rocks. Some analyses were made at my own laboratory, but for the major part of them I am greatly indebted to my co-working expert scientists, the chemists: Dr. Naima Sahlbom, Miss Telma Berggren, Dr. Karl Almqvist and Ragnar Blix; and the spectrographers: Dr. Sture Landergren and his assistant W. Muld. Some quartz-spectrographic determinations have also been made at the Boliden Mining Co. Laboratories, for which I owe sincere thanks to the Management and Staff of that Company. — Finally, the author gratefully acknowledges the generous allocation granted by the State Research Council (Statens naturventenskapliga forskningsråd), which financed the greater part of the investigation of the rock minerals.

Since my above mentioned paper on the distribution of barium was published, the great survey of the chemistry of the earth by K. Rankama and G. Sahama[1] has appeared (3). It contains, however, very few data on the distribution of Ba and Sr in alkaline rocks in addition to those already found in Rankama's earlier paper on the geochemical differentiation in the earth crust (4). Judging by his compilation of existing data, the Ba and Sr contents of alkaline rocks seem to be rather scantlily investigated. According to Engelhardt (1936) nepheline syenites and phonolites contain 520 g/ton Ba, and according to Noll (1934), then existing litterature mentions a quantity of 1200 g/ton Sr in nepheline syenites. As regards the minerals of alkaline rocks, R & S report a content of 2.04 % Ba in orthoclase from nephelinite, 43 g/ton Sr in nepheline, 255 g/ton Sr in leucite, 0.5% Sr in zircon, up to 2% in sphene, 0.4% in catapleite, up to 2% in eudialyte and up to 10% in apatite (admixed Sr-apatite?).

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[1] Hereafter referred to as R & S.

We seem to have obtained our present knowledge from analyses of rocks and minerals chosen more or less at random, no systematic survey of any well defined region having previously been carried out. Although I am also well aware of the inadequacy of the present research work, it may nevertheless serve to throw additional light on the distribution of barium and strontium in co-genetic alkaline rocks and minerals of a specific occurrence.

Table I

	Ba	Sr	Number of analyses		Average g/ton		Ratio
	g/ton		Ba	Sr	Ba	Sr	Sr : Ba
Migmatites							
Gneiss-granite	90— 90	<26	2	1	90	<26	<0.29
Schists	540	<26	1	1	540	<26	<0.05
Fenites							
Melanocratic	<45— 630	<26	3	2	270	<26	<0.10
Mesocratic	630—1 630	85	2	1	1 080	85	0.08
Leucocratic	360—4 120	40 – 420	4	3	2 240	230	0.10
Alkaline intrusives							
Melanocratic	720—3 140	0— 50	4	4	1 790	20	0.01
Mesocratic	450 -2 960	85—2 110	4	3	2 420	1 050	0.43
Leucocratic	2 240—5 550	850—1 020	4	2	4 210	935	0.22
Sövites, rich in biotite	2 340—2 610	<45	2	2	2 480	<45	<0.01
Sövites, poor » »	450— 630	25— 120	2	2	540	~60	0.11
Sövite, rich in serpentine	450	120	1	1	450	120	0.27
Dike rocks							
Alnöites	720—2 240	90— 340	4	5	1 700	270	0.16
Ouachitites, Kimberlites	2 330—2 420	45— 540	3	2	2 390	270	0.11
Nepheline-porphyries	720—3 230	85—1 020	3	4	2 390	595	0.25
Beforsites (dolomitic carbonatites)	<45—5 470	45—6 260	7	15	2 380	1 030	0.43
Beforsites (strontianite-bearing dike excluded)		<45—2 540		14	2 320	660	0.29
Alvikites (calcitic carbonatites)	270—6 900	<25—2 115	8	12	2 390	400	0.17

The new determinations of the Ba and Sr contents of the rocks are given in Table I. Comparison may first be made between those of the archaean migmatites surrounding the Alnö alkaline rock-area, and R & S's compilation of corresponding rocks. The Ba content of the gneiss-granite is then found to be very much lower, only 1/7th of the Finnish granites listed by R&S, and this applies also to the Sr content. In the case of the schists the Ba content of the Alnö biotite-schists as compared with that of the aluminium-rich schists of southern Finnish Lapland is of the same magnitude, while the Sr content is very much lower. As the schists constitute a subordinate part of the migmatites, it may be said that, in general, the archaean migmatites surrounding the alkaline rocks at Alnö are poor in Ba and very poor in Sr. This is contrary to my previous erroneous statement (2, p. 47), claiming agreement in respect of the Ba contents of the [illegible] magmatites with the Ba contents of the [illegible] rocks in Rankama's compilation. Finally, the comparatively very high percentages of Ba and Sr within the [illegible] as well as within the [illegible] alkaline rocks [illegible] cannot originate from any [illegible] of the country rocks and [illegible] of the [illegible]. [illegible] have been introduced by way of the liquids of the [illegible].

Within the [illegible] and ultimately [illegible] magmatites, [illegible] the [illegible], the so-called [illegible], a very strong enrichment in both Ba and Sr is noted, [illegible] Ba/Sr [illegible]. A study of the attached Table II, giving the Ba and Sr contents of the rock minerals, shows that [illegible] [illegible] [illegible] Table III [illegible] by Fig. 1 is obtained.

It may be concluded from the above that the Sr [illegible] the substitution of Ba for K, although [illegible] limit [illegible] by the [illegible] Ba and K from the [illegible].

In the case of the "intrusive" rocks [illegible] values of Ba and Sr are registered. However, the "intrusive" rocks [illegible].

The Sr/Ba ratio does not show, as in the case of the [illegible] values from [illegible] rocks, [illegible] Ba content, while the Sr content [illegible] is explained by the Sr and Ba content of the [illegible] minerals compiled in Table II.

While the soda-orthoclase of these rocks contain an average of about [illegible] g/ton Ba and [illegible] g/ton Sr, the nepheline, [illegible] is extremely poor in strontium. [illegible] of the nepheline [illegible] the [illegible] content of the mineral [illegible]. The Ba/Sr [illegible] the [illegible] rock will [illegible] depend on the percentage of [illegible]. In some cases, when [illegible] altered nepheline [illegible] is present, the Ba content may be slightly raised.

Within the [illegible] rocks the [illegible] percentage is generally higher than in the [illegible] rocks [illegible] in the [illegible], which contains practically no barium, but a percentage of strontium of the same order as that of the [illegible]. The [illegible]

Table II

Contents given in g/ton

	Fenites		Intrusives		Carbonatites (sövites and dikes) Barite dikes		Alnöites		Ratio
	Ba	Sr	Ba	Sr	Ba	Sr	Ba	Sr	Sr : Ba
Amphibole									
(brown hornblende)							360	90	0.25
Apatite									
fenite, Pottäng					1 880	260			0.14
sövite, Stolpås, rich in apatite					1 790	170			0.10
sövite, Stavsätt, » » »					1 350	170			0.12
sövite, Smedsgården, poor in apatite					720	<85			<0.12
jacupirangite, Ås			810	85					
Barite									
Pottäng quarry					583 830	260			0,0004
Hartung »					562 510	510			0.0009
Biotite									
in sövite					6 360	<85			<0.01
» »					4 930	<42			<0.01
» »					1 700	<42			<0.02
» »					2 960	<42			<0.01
» »					4 930	<42			<0.01
» alvikite					4 840	<42			<0.01
» beforsite					2 050	<42			<0.02
» alnöite, Stornäset							4 750	<42	<0.01
Calcite									
in sövite, Smedsgården					<45	<42			
Cancrinite									
in juvite dike, Hörningsholm			450	930					2.06
Feldspars									

» » juvite, Ås			14 520	250					0.17
» » metasomatically formed	3 320	<42							<0.01
Feldspars									
metasomatically altered into:									
montmorillonite, mica	2 240	700							0.31
natrolite, mica	1 520	350							0.23
Melanite									
juvite, Ås			450	<85					<0.19
melteigite, Hörningsholm			360	90					0.25
malignite, Ås			540	<42					<0.08
fenite at Pottäng	270	42							<0.16
Nepheline									
intact, $\mathrm{Ne}_{80}\mathrm{Kp}_{20}$			<45	<42					
» $\mathrm{Ne}_{69}\mathrm{Kp}_{31}$			450	<42					<0.09
altered, partly hauyn & nosean			630	25					0.04
» hydrated			<45	<42					
metasomatically formed	3 320	200							0.06
Pyroxenes									
Diopsidic augite, Sövite, Smedsgården					270	<42			<0.16
Augite					<45	<42			
Aegirine-augite, pyroxene-sövite					<45	<42			
» » sövite-pegmatite					540	<42			<0.08
» » biotite-sövite					<45	<42			
» » melteigite			<45	<42					
» » jacupirangite			180	<42					<0.23
» » malignite			180	90					0.50
» » fenite, inner zone	90	<42							<0.47
Serpentine									
serpentine-sövite					<45	170			>3.78
Titanite (sphene)			<45	340					>7.56
Wollastonite									
fenite, inner zone, Pottäng	50	420							8.40

Table III

	g/ton		% weight	
	Ba	Sr	CaO	K_2O
Metasomatically altered feldspar	2 240	700	3.85	7.23
» » »	1 520	350	2.39	5.50
Metasomatic nepheline	3 320	200	0.97	7.37
Metasomatically generated soda-orthoclase	3 320	<42	0.08	14.32

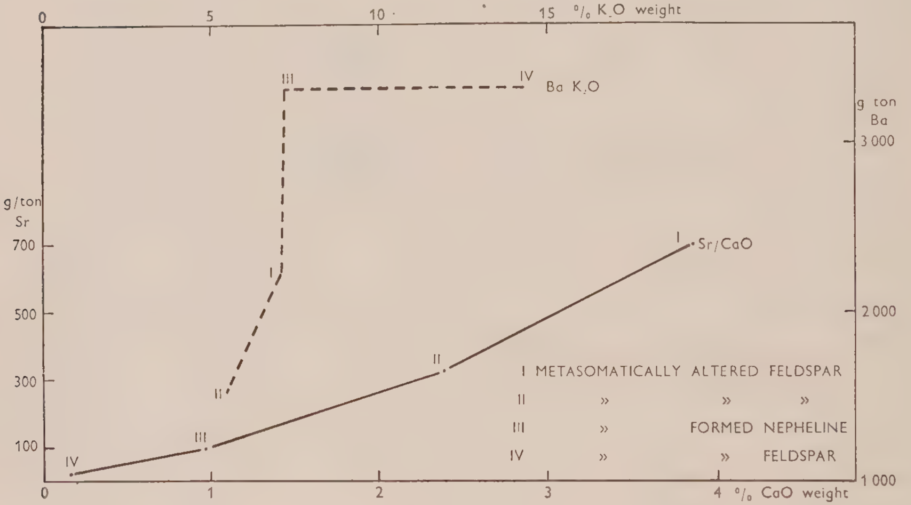

Fig. 1.

very poor in Sr, but an analysis of the mineral taken from a mesocratic malignite indicates a somewhat higher content than in other cases. The melanite on the other hand shows no great variation of Ba and Sr content, that of the latter being very low. This agrees with R & S's statement that calciumgarnets are low in Sr (p. 173). The Ba-content, which at its maximum value is about twice that of the melanite in the fenites, may replace potassium, as the garnets in question contain about 0.2–0.4 % K_2O. Accordingly, the mineral paragenesis may be considered as being responsible for the mesocratic rocks in this case displaying about the same Sr-contents as the leucocratic ones and, in consequence showing a higher Sr : Ba-ratio.

However, one disparity between rock and mineral analyses may be noted in both cases. The numerical average Sr-content of the rocks, 935 1 050 g/ton, is considerably higher than any one hitherto obtained in the mineral analyses. One may surmise a higher average content of Sr in the cancrinite or sphene, in relation to that shown in one single analysis made in each case. The minute crystals of perowskite occurring in the mesocratic rocks may also contain a high percentage, but as compared with the rock their percentage is so small that they can not appreciably have affected the average content of Sr. Finally, the calcite, often present in several percentages, can not carry much Sr to judge by the analysis of calcite in the carbonatites (Cfr. Table

II). The discrepancy may possibly arise from one of the three analyses of mesocratic rocks entering into the average value, i. e. the one of a highly pegmatitic malignite, being exceptional as it shows a maximum value of 2 110 g/ton Sr. If this analysis is removed, the average Sr value of the two remaining ones sinks to 685 g/ton, which is more in agreement with the mineral analyses. The incongruity of the Sr-content of the leucocratic rocks, however, remains unexplained and calls for additional analytical investigation.

The distribution of the two alkaline earth metals in question between the feldspars of the last crystallized sövite and the non-sövitic nepheline-syenite agrees in the case of Ba well with the general rule as expressed by R & S (3, p. 472): "The potash-feldspars formed during the early steps of the crystallization interval contain, as a rule, more strontium and barium than do the potash-feldspars last to crystallize, in which the potassium is relatively enriched". While the former contains an average of about 12 600 g/ton Ba, the latter only shows 6 225 g/ton. As for the Sr, the average is 340 and 380 g/ton, respectively; that is to say, an increase, even though it be a very small one. The aberration may in this case be due to the abnormal composition of the rock last to solidify; to its being more or less pure carbonate and to the ensuing strontium-calcium diadochy of the lime-bearing minerals.

On the other hand confirmation of R & S's statement was obtained in the case of single crystals, by an approximate analysis of kernels of the soda-orthoclase of a sövitic nepheline-syenite dike at Pottäng (Cfr. Table II), previously found to contain 6 000 g/ton Ba and 340 g/ton Sr. Twenty feldspar crystals with an average length of about 10 mm each, were reduced to about one half of their volume by grinding off their outer "shells". The remaining 4 961 grams were found to contain about 7 400 g/ton Ba and 420 g/ton Sr, meaning that the Sr : Ba-ratio remained unchanged during crystallization, although the total percentage of Sr + Ba did sink.

A corresponding investigation was made of the soda-orthoclase from the fenite, previously found to contain 3 320 g/ton Ba, — only, in this case the Sr was not determined. The Ba content of the kernel was found to be lower, about 2 250 g/ton, which phenomenon is quite consistent with the metasomatic introduction of Ba (together with K) at slowly increasing temperature and pressure during the gradual recrystallization of the original feldspar. Incidentally, this confirms my previous deduction (1) as to the metasomatic genesis of the syenitic (and partly nepheline-bearing) rocks surrounding the alkaline intrusive which by earlier investigators were assumed to be magmatic.

Finally, before leaving the intrusive rocks of "abyssic" character, it is necessary to alter a previous statement in my preliminary communication (2, p. 47). The average Ba-content of the sövites is not strictly equivalent to that of the mesocratic nepheline-bearing rock as previously found, but approaches that of the melanocratic rocks. The maximum and minimum values, however, are almost equivalent to those of the mesocratic rocks.

The Ba of the sövites seems to be carried mainly by the biotite, the Ba percentage of the various pyroxenes being negligible. The average content found in the sövites rich in biotite, 2 480 g/ton Ba, agrees fairly well with the average of the corresponding biotites, 5 645 g/ton Ba, considering that the sövites contain up to 32% biotite (Cfr. for instance 1, analyses 50, 51). The two analyses of Table II from sövites of moderate biotite content confirmingly show a lower average: 540 g/ton Ba.

The Sr of the sövites, on the other hand, is undoubtedly of a higher concentration in the sövites poor in biotite and is, consequently, not harboured by this mineral.

The apatite may contain it, but this supposition has not been verified by analysis. Nevertheless, the analyses of apatite from the Stolpås sövite[1] quarries strongly suggests it. An item of interest in this connection is a sövite (from Stavsätt) rich in serpentine-pseudomorphs of olivine (Cfr. Table I), which shows a remarkably high Sr : Ba-ratio (0.27). The analysis of the serpentine (Cfr. Table II) discloses an almost total absence of barium and presence of strontium to a fair degree. This may be explained by a Sr-Ca-diadochy within the original monticellitic olivine.

If we now turn to the dike rocks of hypabyssal character we do not find the same regularity of distribution between leucocratic and melanocratic rocks. The maximum values of Ba and Sr may be arranged in a rising series and in different ones for the two metals as shown by the varying Sr : Ba-ratio, but not so the minimum or average ones. This becomes understandable when bearing in mind that while the "abyssal" rocks are all samples of contemporaneous equilibria at one and the same intrusion level, now uncovered by erosion, the dike rocks of cone-sheet character, although sampled at the very same level, have travelled different and far greater distances from their respective foci, in shorter time than the more slowly rising magma column of the central conduit. The fractures of the wall rocks, caused by explosive shattering due to sudden increase in internal CO_2-pressure, were probably very rapidly filled by the magmatic liquid forced out from the respective cone-sheet foci. The examination of the rocks resulting has led to the deduction that in most cases very little alteration has taken place during their "mise en place", bar some carbonatization.

As already pointed out in my preliminary communication it is therefore of very great interest to note the almost constant average value, 2 320–2 390 g/ton Ba, of all the dike rocks except the most femic and deep-seated ones, the alnöites. This value is almost equal to the Ba value of the mesocratic "abyssic" intrusives and the leucocratic fenites. It not only confirms the rapid consolidation of the dikes, but suggests also a corresponding percentage of BaO in the main intrusive body at the depth of the cone-sheet foci. As for the strontium the content is of the same magnitude in the nepheline porphyries and carbonatites, if the unique strontianite-bearing dike at Stavreviken Bay (on the main land) is excluded, varying from 410 to 595, which means that the Sr : Ba-ratio of the three groups of dikes is almost constant. The Sr-contents of the ouachitites and kimberlites are, on the other hand, equal and the Sr : Ba-ratio correspondingly different.

This may be comprehensible when recalling that the kimberlites as well as the ouachitites are chemically of about the same composition as the alnöites (Cfr. 1, Fig. 30, p. 109), but on an average slightly more potassic at equal lime content. A somewhat higher Ba-content due to a facilitated K-Ba-diadochy and an equal Sr-one may, in consequence, be expected.

The main carrier of the Ba seems again to be the biotite (Cfr. Table II), while the Sr may be supposed to be trapped in either the apatite or the melilite or both, as neither the biotite nor the hornblende contains over 0.01 %. Unfortunately the separation of these two microscopic minerals met with such difficulties that it had to be given up. However, a quantitative test on impure concentrate, containing altered melilite, calcite and apatite, clearly indicated the presence of strontium. Some Sr may be harboured, too, by the minute perowskite crystals.

A few words may here be said about the Ba and Sr content of apatite. In my preliminary report the conspicuous increase of apatite in the wall rocks during the last stages of fenitization as well as the higher Ba-content in apatites from sövites rich in apatite were pointed out. Since then three new analyses of the Ba-Sr-contents of apatite have been carried out: One on apatite from the inner fenitized wall rock, one on a sample from the sövite at Stavsätt, rich in apatite, and the third on the apatite of the jacupirangite at the Ås iron ore mines. It may from the results given in Table II be deduced that the rising content of Ba (also to a less degree of Sr) in the apatite of Alnö rocks rich in apatite, is not accidental and that this phenomenon may simply be due to the absence in the rocks poor in apatite, of minerals rich in potassium viz. biotite and to the presence of other minerals more suitable to a Sr-Ca-diadochy, as for instance monticellite (serpentine), cancrinite and sphene.

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[1] Rich in biotite.

In the case of the rocks rich in apatites, it may furthermore be said that R & S's statement (4, p. 475) that "the behaviour of barium very much resembles the behaviour of strontium, and the rocks rich in one of the two metals are usually rich in the other as well," is moderately true. This is, however, as we have already seen, not always so in regard to the Alnö rocks and minerals. Of the discrepancies previously pointed out, that of the low Sr-content of the nepheline of the intrusives is the most striking one. While occasionally harbouring some Ba — though only in small quantities — it never contains any strontium but traces of it. The comparatively low Ba-content of the same mineral is also puzzling, as Ba-nepheline has been synthetically produced by WEYBERG (1909). It may be observed, however, that it did not agree satisfactorily with the formula $R_2Al_2Si_2O_8$.

From what has been said above it is obviously quite clear that the Ba and Sr have concentrated at a late stage of the genesis of the alkaline rocks. No independent barium or strontium mineral formed during the main stage of crystallization has so far been found. At the finishing stage of solidification, however, strontium has in one single place been observed as minute strontianite crystals in a carbonatitic dike, containing as accessories chalcedonite, barite and free CO_2 (Cfr. 1, analysis Nr. 97). As to the barium, it occurs occasionally as barite in all the alkaline rocks of the late stages of crystallization, but was discovered by the author of this article in concentration on a large scale as barite veins within zones of post-magmatic hydrothermal activity (1, p. 82; 2, p. 48). The abundance of fluorite in the marginal parts of every vein bears evidence of the fact that fluorine-bearing gases have played a deciding part in the concentration of the barium.

The Sr-content of this barite is about the same as that of the feldspars, but the exceedingly small Sr : Ba-ratio is of course totally different.

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